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DESIGN AND SIMULATION OF A DYNAMIC
POSITIONING SYSTEM FOR A
U.S. COAST GUARD BUOY TENDER

by

William R. Cairns

September 1989

Thesis Advisor: Harold A. Titus

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Design and Simulation of a Dynamic Positioning System For a U.S. Coast Guard Buoy Tender

by

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

This paper covers the design of a dynamic positioning system for the U.S. Coast Guard WLB "IRIS" class buoy tender. The control system design is based upon optimal control theory with estimates of position and heading provided by a steady state Kalman filter. Sea current estimates are provided by a Kalman filter predictor based upon the innovations process. The vessel and dynamic positioning system are simulated using the Dynamic Simulation Language (DSL).

THESIS DISCLAIMER

The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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I. INTRODUCTION TO DYNAMIC POSITIONING SYSTEMS

A. DEFINITION

A dynamic positioning system (DPS) is an automatic control system that will drive a vessel to a selected position and maintain that position and selected heading using computer control of propulsive thrusters. A DPS includes one or more position and heading measurement systems and a computer-directed control system. The system should keep the vessel within its specified position and heading constraints with optimal use of propulsors, reducing the wear on that machinery.

B. ADVANTAGES AND DISADVANTAGES

The use of DPS is not new. The first dynamic positioning systems appeared in the late 1960's on coring, cable laying and surface-support ships for underwater work. The success of these initial DP vessels spread the application of the systems into offshore oil industry, dredging, precision dumping, pipe laying, and floating hotels.

There are several advantages of dynamic positioning over anchor deployment. It is usable in all water depths and not constrained by the length of its anchor chain. In contrast to anchoring, there is virtually no set-up time required to begin stationkeeping. In order to reach and attain a precision position by anchoring, time and personnel intensive anchoring details must be set. A DPS allows a vessel to attain virtually any position and heading automatically. Due to its dynamic nature, a DPS vessel can work in close quarters with fixed platforms or anchored vessels. A dynamic positioning system is designed to operate in adverse weather conditions

The disadvantages of DPS include high initial capital investment, high fuel costs (over anchoring), high maintenance due to the continuous activation of thrusters, and increased manpower requirements for maintenance.

Dynamic positioning is an effective means of stationkeeping when water depth is too great for anchoring, on-station time will be brief, the vessel is required to be on station in all weather conditions, and accuracy in positioning is more important than cost.

C. EQUIPMENT FOR DYNAMIC POSITIONING SYSTEMS

The equipment needed for a dynamic positioning system includes a wind sensor (velocity and direction), gyrocompass, and a position reference sensor.

There are several position sensors that are employed in DPS designs. They include sensors that determine position, velocity and/or acceleration in some common reference system. The basic position sensor types are taut wire, optical, acoustic beacon, and radio systems.

The taut wire scheme works by lowering a weight to the sea floor by wire rope. The wire is held in constant tension, usually by a constant-tension winch, and any angle deviations from vertical are corrected by thrusters.

Optical positioning systems are of either active or passive design and make use of laser technology. Triangulation of sextant angles provides position information. However, sextants are manually trained by personnel.

Acoustic beacon is the most common positioning system in the offshore industry. This system requires a sea floor beacon and hull-mounted subsurface hydrophones.

In general, standard radionavigation systems such as Loran-C, OMEGA, and Tansit SATNAV do not provide sufficient accuracy for DP systems. The approximate accuracies of these systems are:

- Loran-C - 460 meters,
- OMEGA - 500 meters,
- SATNAV - 25 meters.

[Ref. 1: p. 8-18]

Accuracies of those magnitudes are completely unacceptable for DP systems. The NAVSTAR Differential GPS, however, is able to provide accurate position information to within 3 meters anywhere on the globe. In addition, this system allows vessels to measure velocity using Doppler to accuracies of about 0.1 meters per second. [Ref. 1 : p. 8-18].

For a ship to be dynamically positioned it must use thrusters, sensors, computer, and a control and display system. The thrusters must be able to provide fore and aft, athwartships, and moment control. Sensors provide physical information including position, heading, and wind conditions. The computer uses sensor information and calculates required thruster commands that will position the vessel at the reference position and heading. Controls and displays are required to allow the operator to monitor and control the DP system.

The purpose of this thesis is to design and simulate a dynamic positioning system for a U.S. Coast Guard buoy tender. The dynamic positioning system is designed to be fully automated, performing its functions in varying sea states, wind, and current conditions with its only operator input being the referenced position.

II. BACKGROUND

The U.S. Coast Guard has begun the acquisition process for seagoing and coastal buoy tenders to replace the aging 157 foot WLM class and the 180 foot WLB class tenders. See Figure 1 for a comparison of the old WLB fleet with its successor [Ref. 2: p.7]. One of the requirements for the replacement vessels is a dynamic positioning system. The dynamically positioned vessel must be able to approach, maneuver, and maintain position, within a circle of a 10 meter radius over a fixed point on the earth, alongside floating aids to navigation in restricted channels of shallow, 18 foot deep bays, estuaries, and rivers. The system is required to maintain position in a 30 knot wind of any aspect and 5 knot current within 10 degrees of ship's head [Ref. 3 : p. 15]. This DPS design endeavors to take a modified existing U.S. Coast Guard (USCG) buoy tender using a minimum of additional control and measurement inputs in order to reduce the potential implementation costs. This initial design is a 180 foot WLB "IRIS" class buoy tender. The only modifications to existing vessels are the installation of a stern thruster and Global Positioning System (GPS). The GPS provides real-time positioning information accurate to within three meters anywhere on the globe [Ref. 1 : p. 8-18]. The GPS is a requirement of the replacement buoy tender fleet. The available controls for this design are 200 SHP bow and stern thrusters and 1170 SHP single screw propulsion. System sensor measurements are GPS, gyrocompass, and wind inputs. The multiple mission requirements of the buoy tender, as with all Coast Guard cutters, placed some constraints on the DPS design from the outset. The buoy tender is occasionally called upon to perform some harbor icebreaking duties. It is considered an ice-capable vessel, able to break up to one foot of ice at three knots [Ref. 3 : p. 15]. Ice operations preclude the use of subsurface position sensing devices such as hydrophones and taut wire schemes. In order to clarify the reasoning behind some of the system constraints, a brief qualitative description of buoy tending operations follows.

A. BUOY TENDING OPERATIONS

At the present time, buoy tending operations are at best an inexact science, as is the case in many shiphandling routines. The manual ship positioning techniques of experienced deck officers have been raised to an art form. Put simply, by the use of sextant angles or other "local" points of reference, the vessel is slowly aimed at its intended position. As the distance to the desired location decreases, the engines are slowed or

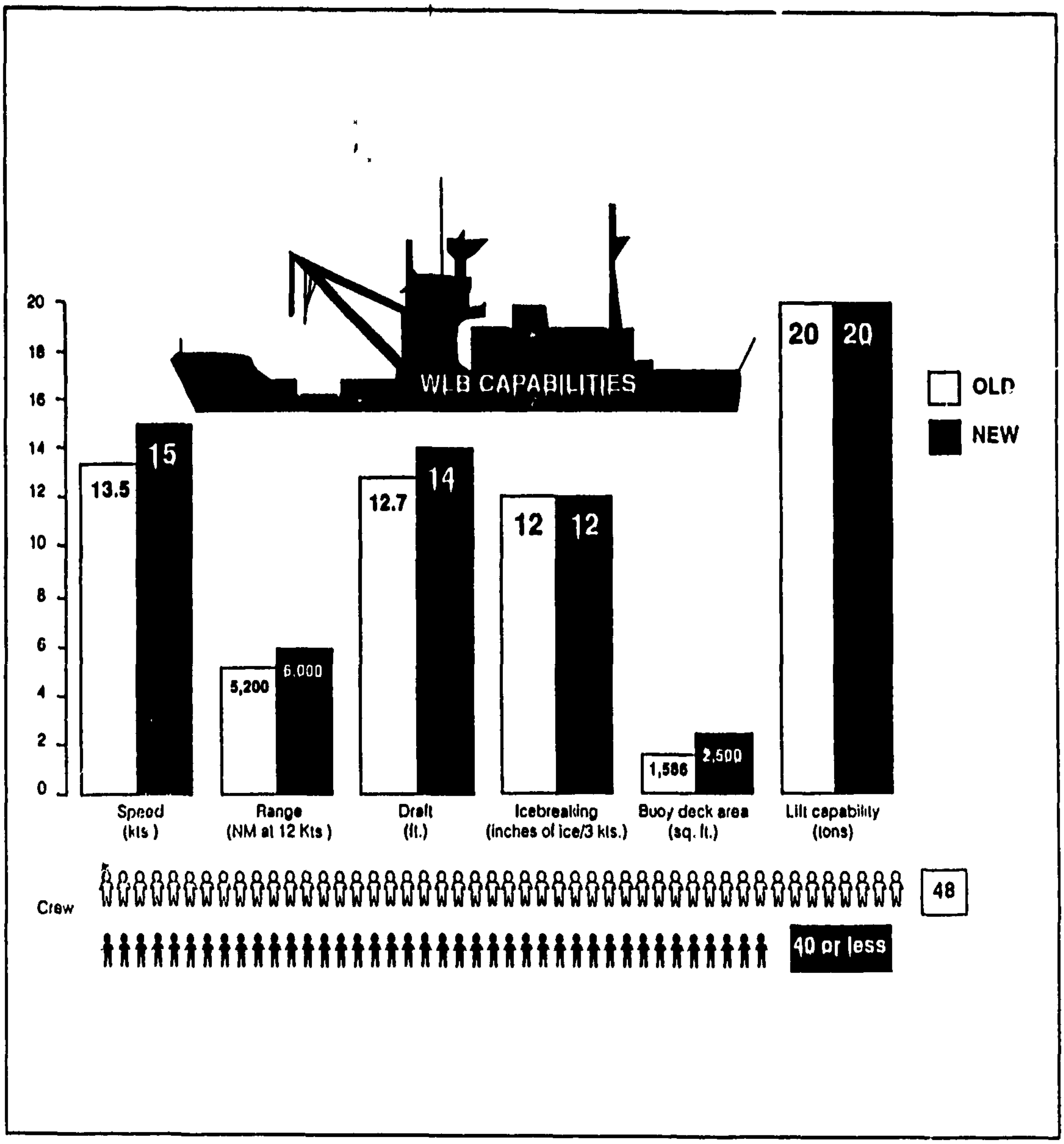

Figure 1. WLB Comparison. (From Ref. 2)

stopped altogether. As the vessel crosses this desired location, the buoy is released in position and the vessel continues on. If, however, the vessel does not cross the desired buoy position, another pass must be made. As weather conditions deteriorate, this procedure can rapidly increase on station time. A dynamically positioned vessel can be programmed for a given location and heading. The DP vessel adapts to environmental changes and makes optimal use of thrusters to maintain position so it clearly has the advantage over the hit-or-miss scenario just described.

III. EQUATIONS OF MOTION

The mathematical modeling of the "plant", the waterborne vessel and its environment, is divided into several parts: low and high frequency vessel models, wind model, and current model.

A. COORDINATE SYSTEM

For modelling purposes, two different coordinate systems are used. Earth-fixed coordinate axes are used to integrate the dynamic equations of motion. A vessel parallel set of axes, with the same origin as the earth-fixed axes, is used for computing the forces acting on the vessel. See Figure 2 for the relationship of these coordinate axes [Ref. 4: p.853]. The x and y axes represent the vessel in surge and sway and the angle ψ is the vessel yaw in degrees true. Hence, heading angle is the same for both sets of axes.

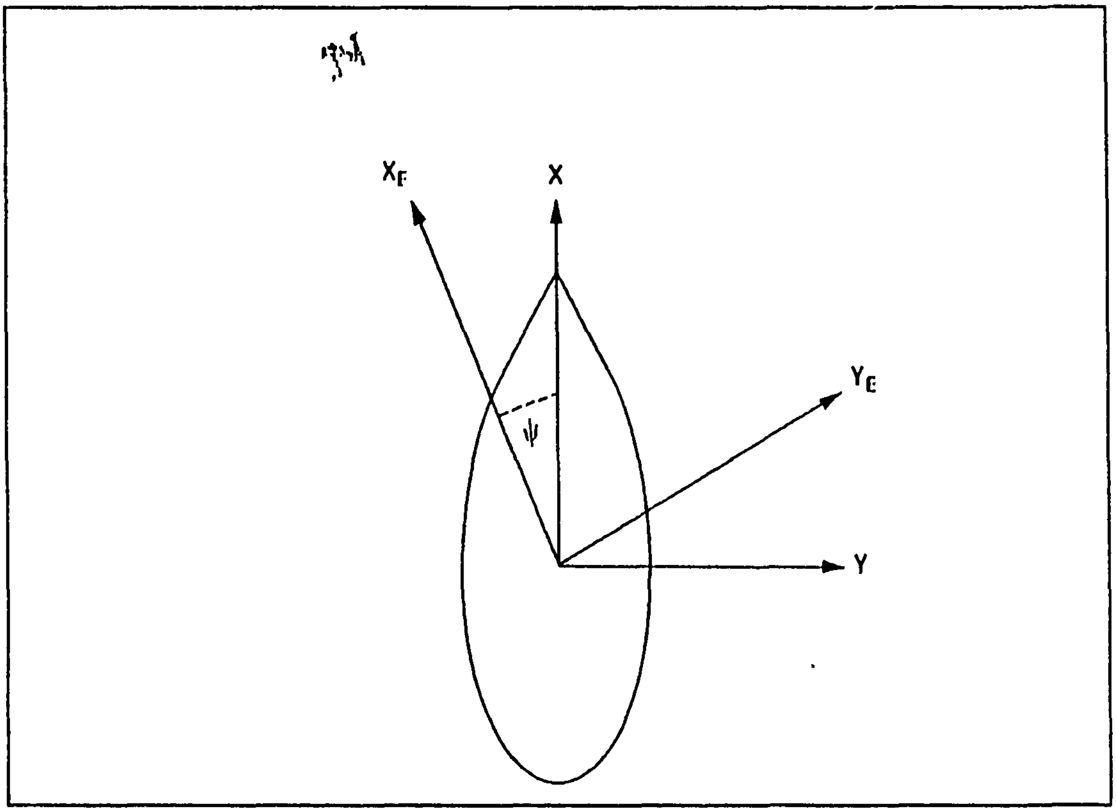

Figure 2. Coordinate Axes

B. LOW FREQUENCY MODEL

The equations of motion for a floating vessel in a seaway are highly coupled and non-linear. Figure 3 is a block diaqram of the low frequency (LF) motions of the vessel in surge, sway, and yaw. The low frequency model represents the dynamic response of the ship in "calm" water with wind, current, and propulsive force disturbances. The effect of wave action is not considered here as that is modeled by the high frequency model below. The coupled non-linear differential equations for surge, sway, and yaw may be expressed as follows:

$$\ddot{x}_L = 1/m_x[m_y(\dot{y}_L)\dot{\psi}_L + m_x v_c \dot{\psi}_L - d_x|\dot{x}_L - u_c|(\dot{x}_L - u_c) + F_{wx} + F_p] + \eta_{Lx} \qquad (1)$$

$$\ddot{y}_L = 1/m_y[m_y u_c \dot{\psi}_L - m_x(\dot{x}_L - u_c)\dot{\psi}_L - d_y|\dot{y}_L - v_c|(\dot{y}_L - v_c) + F_{wy} + F_T] + \eta_{Ly} \qquad (2)$$

$$\ddot{\psi}_L = 1/m_\psi[-(m_y - m_x)(\dot{x}_L - u_c)(\dot{y}_L - v_c) - d_\psi|\dot{\psi}_L|\dot{\psi}_L + M_c + M_w + M_T] + \eta_{L\psi} \qquad (3)$$

where

- $x_L, \dot{x}_L$ - LF surge position and velocity
- $y_L, \dot{y}_L$ - LF sway position and velocity
- $\psi_L, \dot{\psi}_L$ - LF yaw heading angle and angle rate
- u_c, v_c - Current velocities in surge and sway
- F_{wx}, F_{wy} - Wind force in surge and sway
- F_P, F_T - Prop and thruster forces
- M_w, M_T, M_c - Wind, thruster, and current moments in yaw
- $\eta_{Lx}, \eta_{Ly}, \eta_{L\psi}$ - Zero mean Gaussian White Noise Processes
- d_x, d_y, d_ψ - Coefficients of Drag
- m_x, m_y, m_ψ - Effective Mass Terms

[Ref. 4 : p. 853]

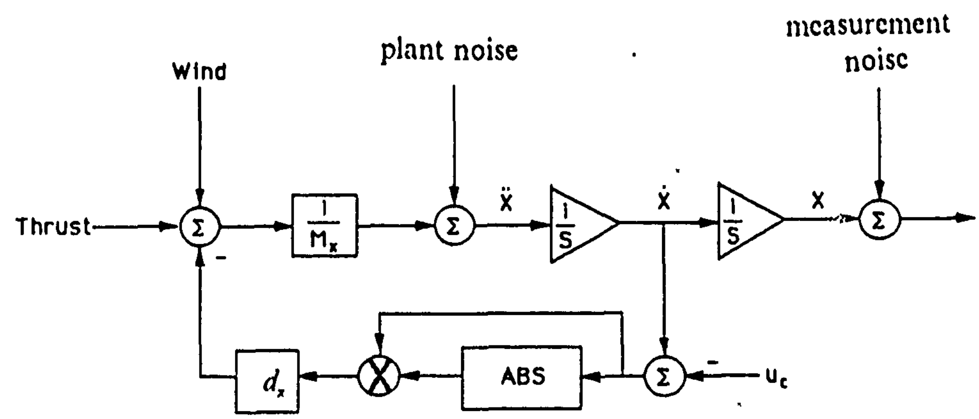

Figure 3. LF Model

C. VESSEL CHARACTERISTICS

As previously stated, the modelled vessel is a USCG WLB "IRIS" class. The vessel is considered to have the following characteristics:

- Length (Overall) - 180 *feet*
- Length (between perpendiculars) - 170 *feet*
- Beam - 37 *feet*

- Draft - 12 *feet*
- Displacement - 943.5 *L.Tons*
- m_x = 71920 *slugs*
- m_y = 147615 *slugs*
- m_ψ = $2.67x10^8$ *slugft²*
- d_x = 169 *slug/ft*
- d_y = 869 *slug/ft*
- d_ψ = $1.17x10^9$ *slugft/rad²*

[Ref. 3 : p. 17]

The effective mass (m_x, m_y, m_ψ) terms are generated by a computer simulation known as the Standard Ship Motion Program (SMP). This program was developed at the David W. Taylor Naval Ship Research and Development Center. The SMP provides predictions of vessel motion in translation (surge and sway) and heading (yaw) in irregular seas based upon strip theory. The effective mass is the sum of the vessel mass (the mass of water displaced by the vessel) and an "added mass" term. The added mass term is predicted by the SMP versus varying frequencies of wave encounter, σ. Appendix A is the printout of the SMP for the 180 foot WLB buoy tender. The added mass and drag terms shown there are non-dimensional. These terms are a function of the frequency of encounter of wave motion, σ, which is also non-dimensional. For purposes of this thesis, constant dimensionalized values of drag and mass are used, based upon an "average" wave frequency of 1.1 radians per second which corresponds to Sea State 5 and an average wave height of 5.0 *ft*. However, the drag terms of the SMP cannot be directly related to the LF equations of motion used here. The drag coefficients are derived directly from Bernoulli's equations for fluid flow on a moving object:

$$F = 1/2\rho U^2 \tag{4}$$

where ρ is the fluid density and U is the velocity of the fluid relative to the object. The drag terms are the product of the Bernoulli force terms with the effective underwater area of the vessel. By using the length between perpendiculars, beam, draft, and a block coefficient of 0.437, the drag terms are as listed above. Simulations using the IODE software package confirm these values. See Appendix B for the simulation results. The vessel is simulated at zero sea state with maximum thrust. Using the effective mass terms of SMP, the drag coefficients are then varied until the known maximum velocities are obtained.

D. HIGH FREQUENCY MODEL

The high frequency vessel model represents the high frequency wave action of the vessel. Three harmonic oscillators are modelled in surge, sway, and yaw with variable frequency, as follows:

$$\ddot{x}_H = -\omega_x^2 x_H + \eta_{Hx} \tag{5}$$

$$\ddot{y}_H = -\omega_y^2 y_H + \eta_{Hy} \tag{6}$$

$$\ddot{\psi}_H = -\omega_\psi^2 \psi_H + \eta_{H\psi} \tag{7}$$

$$\dot{\omega}_x = \eta_{\omega x} \tag{8}$$

$$\dot{\omega}_y = \eta_{\omega y} \tag{9}$$

$$\dot{\omega}_\psi = \eta_{\omega\psi} \tag{10}$$

where

- $x_H, \dot{x}_H$ - HF surge position and velocity
- $y_H, \dot{y}_H$ - HF sway position and velocity
- $\psi_H, \dot{\psi}_H$ - HF yaw angle and angle rate
- $\omega_x, \omega_y, \omega_\psi$ - HF angular frequencies in surge, sway, and yaw
- $\eta_{\omega x}, \eta_{\omega y}, \eta_{\omega\psi}, \eta_{Hx}, \eta_{Hy}, \eta_{H\psi}$ - Zero mean Gaussian White Noise Processes

[Ref. 4 : p.853]

E. WIND MODEL

The wind is modelled as the sum of slowly varying, low mean frequency and rapidly varying high frequency gusts, both in wind speed and direction. The equations for the wind model are:

$$\dot{w}_{vs} = \eta_{wvs} \tag{11}$$

$$\dot{w}_{vf} = a_1 w_{vf} + \eta_{wvf} \tag{12}$$

$$\dot{w}_{ds} = \eta_{wds} \tag{13}$$

$$\dot{w}_{df} = a_2 w_{df} + \eta_{wdf} \tag{14}$$

where the model terms are defined as follows:

- w_{vs} - Slowly varying wind velocity
- w_{vf} - Rapidly varying wind velocity
- w_{ds} - Slowly varying wind direction
- w_{df} - Rapidly varying wind direction
- $\eta_{wvs}, \eta_{wvf}, \eta_{wds}, \eta_{wdf}$ - Zero mean Gaussian White Noise Processes

The wind force terms of equations 1, 2, and 3 are then defined by:

$$F_{wx} = F_1(\beta)(w_{vs} + w_{vf})^2 \tag{15}$$

$$F_{wy} = F_2(\beta)(w_{vs} + w_{vf})^2 \tag{16}$$

$$M_w = F_3(\beta)(w_{vs} + w_{vf})^2 \tag{17}$$

$$\beta = w_{ds} + w_{df} - (\psi_L + \psi_H) \tag{18}$$

where

- F_{wx}, F_{wy}, M_w - Wind forces and moment
- β - Wind angle of attack
- F_1, F_2, F_3 - Effective wind surface areas

[Ref. 4 : p. 854]

The F_i terms are again derived from Bernoulli's equations for fluid flow. In this case the fluid is air and the area is the effective area of wind resistance of the vessel.

F. CURRENT MODEL

The current model is described by the following set of differential equations:

$$\dot{x}_{CE} = \eta_{xCE} \tag{19}$$

$$\dot{y}_{CE} = \eta_{yCE} \tag{20}$$

$$\dot{\psi}_{CE} = \eta_{\psi CE} \tag{21}$$

$$u_c = x_{CE} \cos \psi + y_{CE} \sin \psi \tag{22}$$

$$v_c = -x_{CE} \sin \psi + y_{CE} \cos \psi \tag{23}$$

with the terms defined as follows:

- x_{CE}, y_{CE} - Current velocities in earth coordinates (North and East respectively)
- u_c, v_c - Current velocities in surge and sway

[Ref. 4 : p. 854]

These wind, current, high frequency, and low frequency models constitute the vessel "plant". Each model represents a different aspect of the plant dynamics. It is clear, however, that the only model which may be controlled by the DP system is the low frequency model.

IV. CONTROL SYSTEM DESIGN

A. PROPULSORS

The design of the buoy tender control system is based on several constraints. First, there are only three propulsive forces available: the propeller for thrust forward and astern ($\pm x$ direction, surge) and the bow and stern thrusters for moment control ($\pm\,\psi$ direction, yaw) and athwartships motion ($\pm$ y direction, sway).

The bow and stern thrusters are 200 HP fixed tunnel units. A good rule of thumb for the thrust developed by fixed azimuth tunnel thrusters is $30\,ft\;lbf/SHP$. These will yield approximately 6000 pounds force in the $\pm$ y direction. The bow thruster is located 78.88 feet forward of the center of buoyancy and the stern thruster is 81.12 feet astern of it. See Figure 4 for the thruster layout.

The force and moment equations for the bow and stern thrusters are thus:

$$FT = BT + ST \tag{24}$$

$$MT = 78.88BT - 81.12ST \tag{25}$$

where,

- FT - Athwartships force due to thrusters
- MT - Yaw moment due to thrusters
- BT - Force of bow thruster
- ST - Force of stern thruster

It must be noted that athwartships force, FT, is assumed to be applied at a single point, the center of buoyancy. The moment force, MT, is applied about the center of buoyancy by the thrusters proportional to their output and the length of the moment arm. This length is measured from the center of buoyancy to the thruster. A positive moment is considered to be one which will make the ship turn to starboard, a negative moment to port. See Figure 4 for the thruster moment dimensions.

The fixed pitch propeller is driven by a single 1170 SHP diesel electric power plant. It can normally produce upwards of 20,000 pounds force of thrust. The equation for the maximum thrust generated by the propeller is:

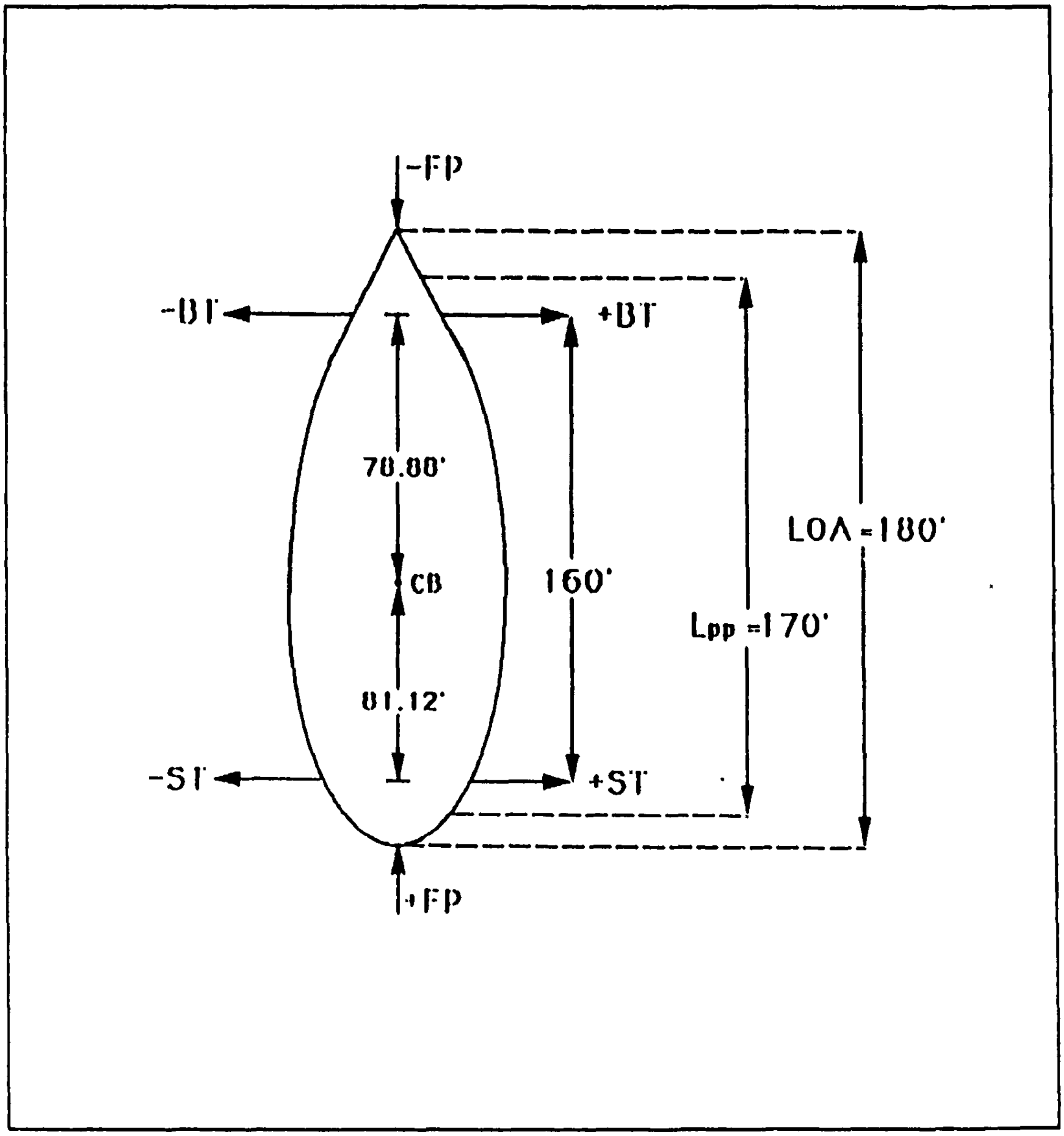

Figure 4. Thruster Forces and Moments

$$FP_{\max} = \frac{\eta_{prop} SHP_{\max} [550 \frac{ft\ lbf}{HP}]}{V_{\max}} \tag{26}$$

Assume a propeller efficiency, $\eta_{prop} = .75$ and a maximum velocity, $V_{\max} = 14.3\ knots$, this yields a maximum thrust $FP_{\max} = 20{,}250\, ft\ lbf$. However, due to the nature of positionkeeping, the propeller controller was limited to 12,000 pounds force in the DP mode.

The controller design is based only on the low frequency vessel model. Responding to the high frequency wave action of the vessel would cause the controllers to modulate in even moderate seas.

The low frequency system was placed in state variable format,

$$\dot{x} = Ax + Bu + Gw \tag{27}$$

$$y = Cx + Du + v \tag{28}$$

The non-linear, coupled A and B matrices are:

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & -d_x|\dot{x} - u_c|/m_x & 0 & m_y\dot{\psi}/m_\psi & 0 & v_c \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & -m_x\dot{\psi}/m_y & 0 & -d_y|\dot{y} - v_c|/m_y & 0 & u_c \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & -(m_y - m_x)\dot{\psi}/m_\psi & 0 & -(m_y - m_x)\dot{x}/m_\psi & 0 & -d_\psi|\dot{\psi}|/m_\psi \end{bmatrix} \tag{29}$$

$$B = \begin{bmatrix} 0 & 0 & 0 \\ 1/m_x & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 1/m_y & 1/m_y \\ 0 & 0 & 0 \\ 0 & 78.88 & -81.12 \end{bmatrix} \tag{30}$$

The state observations matrix, C is:

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \tag{31}$$

The low frequency plant is linearized about

$$u_c = v_c = \dot{\psi} = \dot{x} = \dot{y} = 0 \tag{32}$$

and the vessel parameters substituted to yield the linear A, B, and G matrices.

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{33}$$

$$B = \begin{bmatrix} 0 & 0 & 0 \\ 1.39E-05 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 6.77E-06 & 6.77E-06 \\ 0 & 0 & 0 \\ 0 & 78.88 & -81.12 \end{bmatrix} \tag{34}$$

The plant noise matrix is:

$$G = \begin{bmatrix} 0 \\ .0005 \\ 0 \\ .0005 \\ 0 \\ .0005 \end{bmatrix} \tag{35}$$

The state variable matrix is:

$$x = \begin{bmatrix} x \\ \dot{x} \\ y \\ \dot{y} \\ \psi \\ \dot{\psi} \end{bmatrix} \tag{36}$$

The control matrix is:

$$u = \begin{bmatrix} FP \\ BT \\ ST \end{bmatrix} \tag{37}$$

The Control Toolbox of the software package PC-MATLAB (for MS-DOS Personal Computers, Version 3.2-PC June 8, 1987) is then used to obtain the feedback gains. Assuming full state feedback is available, the lqr (linear quadratic regulator) function calculates the optimal feedback gain matrix K_{opt} such that the feedback law:

$$u = -K_{opt}x \tag{38}$$

minimizes the cost function:

$$J = \int (x^T Q x + u^T R u) dt \tag{39}$$

where the state weighting matrix, Q is:

$$Q = \begin{bmatrix} 3E04 & 0 & 0 & 0 & 0 & 0 \\ 0 & 3E04 & 0 & 0 & 0 & 0 \\ 0 & 0 & 6E04 & 0 & 0 & 0 \\ 0 & 0 & 0 & 6E05 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1E09 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1E09 \end{bmatrix} \tag{40}$$

and the control weighting matrix, R is:

$$R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{41}$$

The lqr function returns the following feedback gains:

$$K_{opt} = \begin{bmatrix} 173 & 4977 & 0 & 0 & 0 & 0 \\ .0 & 0 & 150 & 4434 & 24962 & 249962 \\ 0 & 0 & 193 & 5701 & -19415 & -19415 \end{bmatrix} \tag{42}$$

This places the eigenvalues of the closed loop linearized system at:

$$s = \begin{bmatrix} -0.035 \pm j0.035 \\ -0.034 \pm j0.034 \\ -1.0 \\ -3.6E06 \end{bmatrix} \tag{43}$$

Since all the states are not available for feedback, an observer is utilized to provide an estimate of the states. A Kalman filter is designed with the aid of the PC-MATLAB function lqe (linear quadratic estimator). Recall the system:

$$\dot{x} = Ax + Bu + Gw \tag{44}$$

and

$$y = Cx + Du + v \tag{45}$$

where the expected values of the plant noise, w, and the measurement noise, v, are $E[w] = E[v] = 0$ and the covariance matrices for plant and measurement noise are, respectively, $E[ww']$ and $E[vv']$. The covariance matrices are:

$$E[ww'] = 0.0005 \tag{46}$$

$$E[vv'] = \begin{bmatrix} 100 & 0 & 0 \\ 0 & 100 & 0 \\ 0 & 0 & .0003 \end{bmatrix} \tag{47}$$

The lqe function returns the Kalman filter gains, K, for the equation:

$$\dot{\hat{x}} = A\hat{x} + Bu + K(y - C\hat{x}) \tag{48}$$

where $\hat{x}$ is an estimate of x. The Kalman gain matrix, K, is:

$$K = \begin{bmatrix} 0.0669 & 0 & 0 \\ 0.0022 & 0 & 0 \\ 0 & 0.0669 & 0 \\ 0 & 0.0022 & 0 \\ 0 & 0 & 1.6069 \\ 0 & 0 & 1.2910 \end{bmatrix} . \tag{49}$$

The output of the Kalman filter is the sum of the nonlinear low frequency system, including sampled values of position, heading, and wind velocity and direction, with the Kalman updates of position. The sampled wind velocity and direction data is transformed into ship's coordinates and forces the vessel Kalman filter exactly, within sampling error, as the true wind forces the low frequency model. The optimal feedback gains are then used with the Kalman filter output to create the optimal Kalman filtered control:

$$u = K_{opt}\hat{e} \tag{50}$$

The reference error matrix, $\hat{e}$, is defined by:

$$\hat{e} = \begin{bmatrix} r_x - \hat{x} \\ r_{\dot{x}} - \hat{\dot{x}} \\ r_y - \hat{y} \\ r_{\dot{y}} - \hat{\dot{y}} \\ r_\psi - \hat{\psi} \\ r_{\dot{\psi}} - \hat{\dot{\psi}} \end{bmatrix} \tag{51}$$

The r values here represent the reference positions, heading, and associated velocities. The reference positions and heading are the desired location of the vessel. Since the desired location is to be maintained, clearly the reference velocities must be zero.

These optimal controls are then passed to a non-linear filter. This non-linearity is a limiter which prevents the thrusters and main propulsion from exceeding the maximum DP mode limits (i.e., 12,000 *lbf* for main propulsion and 6,000 *lbf* for thrusters).

It is readily apparent that the control system as designed does not correct for the steady state error caused by the introduction of current. A modification to the control design to compensate for current offset is imperative. A Kalman filter predictor of current is designed based upon the residual error in the vessel position estimator. That is, the difference in estimated and measured position and heading is assumed to be due to current. This is the "measured" value of the Kalman current filter. Recall the Kalman filter equation:

$$\dot{\hat{x}} = A\hat{x} + Bu + K(y - C\hat{x}) \tag{52}$$

For the current predictor filter:

$$\hat{x} = \begin{bmatrix} \hat{x}_c \\ \hat{u}_c \\ \hat{y}_c \\ \hat{v}_c \\ \hat{\psi}_c \\ \hat{M}_c \end{bmatrix} \tag{53}$$

$$y = \begin{bmatrix} x_T - \hat{x} \\ y_T - \hat{y} \\ \psi_T - \hat{\psi} \end{bmatrix} \tag{54}$$

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \tag{55}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \tag{56}$$

The current estimator covariance matrices are:

$$E[ww']_c = 0.00002 \tag{57}$$

$$E[vv']_c = \begin{bmatrix} 5 & 0 & 0 \\ 0 & 5 & 0 \\ 0 & 0 & .005 \end{bmatrix} \tag{58}$$

The current estimation filter gain matrix, K_c, is:

$$K_c = \begin{bmatrix} 0.0140 & 0 & 0 \\ 0.0044 & 0 & 0 \\ 0 & 0.0140 & 0 \\ 0 & 0.0044 & 0 \\ 0 & 0 & 6.0000 \\ 0 & 0 & 18.200 \end{bmatrix} \tag{59}$$

The terms x_T, y_T, and ψ_T are the observations of surge, sway, and yaw including high frequency wave action and measurement noise. The estimates of current are converted to force terms by Bernoulli's equation and subtracted from the appropriate thruster control commands. Figure 5 shows the final system control design in block diagram form.

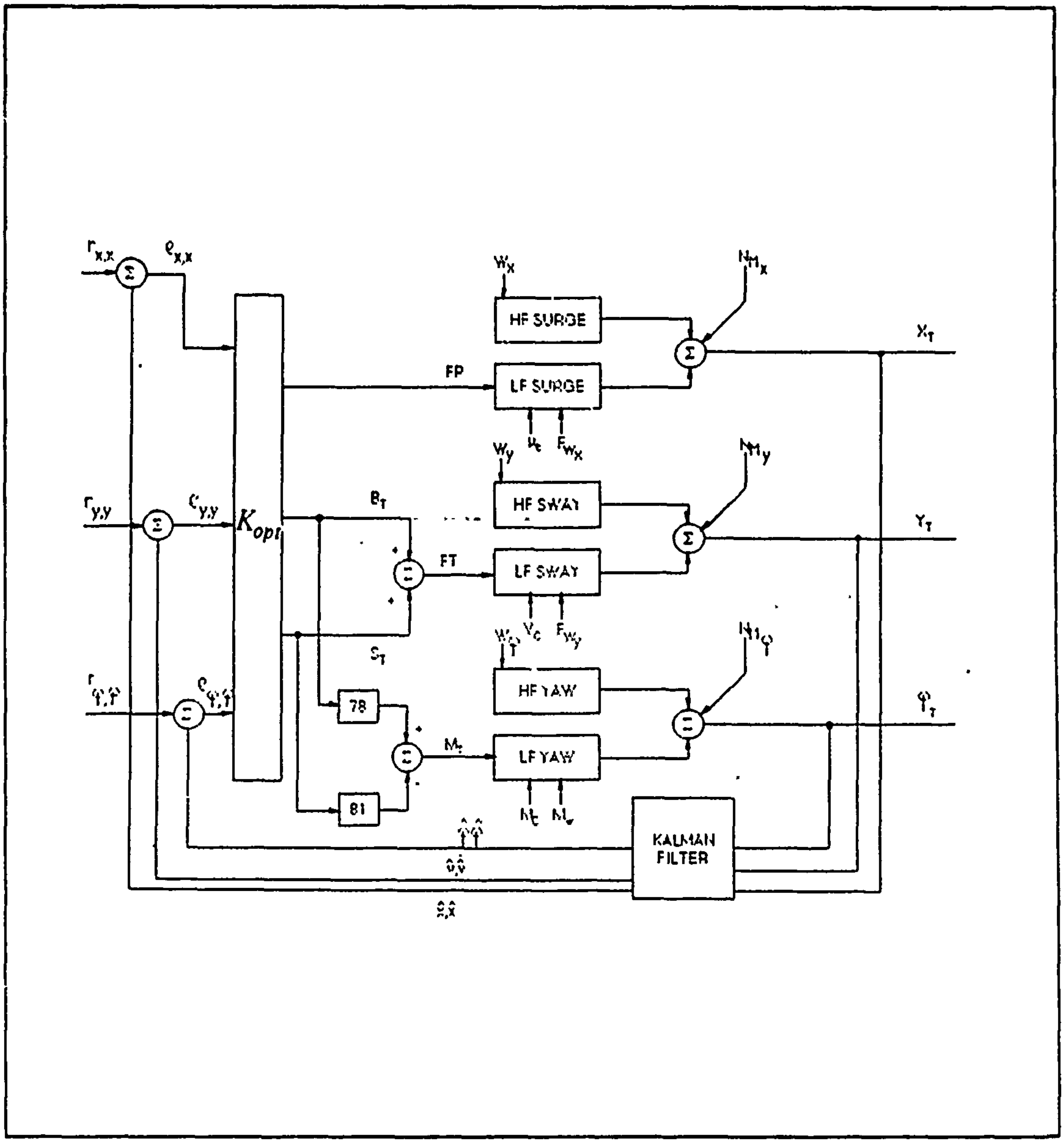

Figure 5. Control System Design

V. COMPUTER SIMULATION

The equations of motion and control system discussed in previous chapters were implemented using the Dynamic Simulation Language/VS (DSL). It is a high level continuous simulation language developed by IBM which incorporates VS FORTRAN as a subset. The program is included in Appendix C here as an immediate reference. Comments are included as additional documentation. DSL was used here since it is a high level language which models the system in continuous time. Although the system is modeled as an analog system, DSL allows for the sampling of data as well. This sampling was used with the position, heading, and wind measurements, which were updated at 1 second intervals. Nearly all of the various models require Gaussian noise inputs which are represented by the NORMAL function. This function has inputs of seed number, mean, and standard deviation. One final word on DSL is that it has its own plotting routine. System outputs presented here were printed using this plotting package.

VI. RESULTS

The simulation results of the dynamically positioned buoy tender are shown here in a number of different environments. As discussed previously, the specifications for the desired dynamic positioning system are ambitious. To review, the vessel is to attain and maintain position to within a 10 meter radius in 30 knots of wind in any aspect and 5 knots of current within 10 degrees of the bow. The initial test of the simulation is with no current, no wind, and at sea state 0. These conditions introduce the least amount of disturbance into the system. As can be seen from Figure 6, the vessel holds position in surge to within 5 feet. Similarly, Figure 7 and Figure 8 show the vessel holding sway position within 5 feet and a decaying exponential response in yaw angle, with its maximum overshoot of 0.05 radians. In each graphical presentation of vessel position and heading, the true-measured position and heading are plotted along with the respective vessel Kalman filter estimates. A position plot is shown in Figure 9. The position plot is presented as an "overhead" look at the vessel track in vessel coordinates. in order to obtain this vessel response, a conservative use of propulsive force is used, as witnessed in Figure 10 and Figure 11.

The system is again simulated at sea state 0 with no wind and a current of 3 feet per second. In Figure 12 the system performance is observed in the surge direction. Since the vessel estimator is not forced by the current estimator, there is a bias introduced by the vessel estimator. This bias could be corrected by modifying the state variable matrix with the current velocities in surge and sway such that:

$$x = \begin{bmatrix} x \\ \dot{x} - u_c \\ y \\ \dot{y} - v_c \\ \psi \\ \dot{\psi} \\ \dot{\psi} \end{bmatrix} \tag{60}$$

This bias is exactly balanced in the propulsion scheme by the current estimated force. Similarly, the system performance in sway, Figure 13, and yaw, Figure 14, is within the system constraints in the presence of this current. The position plot, Figure 15, closely resembles its counterpart for the zero current case. However, the overshoot in both surge and sway is even more apparent in this plot. The transient performance is not of particular importance as the steady state performance is acceptable. Due to the continuing nature of the current disturbance, non-zero propulsive force., result in the steady state as seen in Figure 16 for main propulsion force and in Figure 17 for bow and stern thruster forces.

The vessel when simulated at a current velocity of 4 feet per second does not maintain its desired position due to the steady state saturation of the bow and stern thrusters. The maximum current for which this system is effective is considered to be 3 feet per second.

Since fully developed seas are correlated with wind velocity, the final simulation is at sea state 5 with current of 3 feet per second and 30 knot winds. With the addition of the Kalman predictor for current and the fact that wind is sampled each second and is incorporated into the vessel position Kalman filter, no great degradation in system performance is anticipated. The surge, sway, and yaw performance of the vessel can be seen in Figure 18, Figure 19, and Figure 20, respectively. The vessel response in surge and sway are well within the specifications. Although thers is no requirement to maintain vessel heading, the steady state yaw response of the vessel is held to about 0.2 radian of the reference. The load on the propulsors under these conditions is heavy as can be seen in Figure 21 and Figure 22. The position plot of the vessel under these conditions is seen in Figure 23. The steady state position is still within the vessel specifications.

Although there is a degradation in system performance with increased environmental disturbances, the vessel is able to maintain a desired position to within the constraints imposed at the outset.

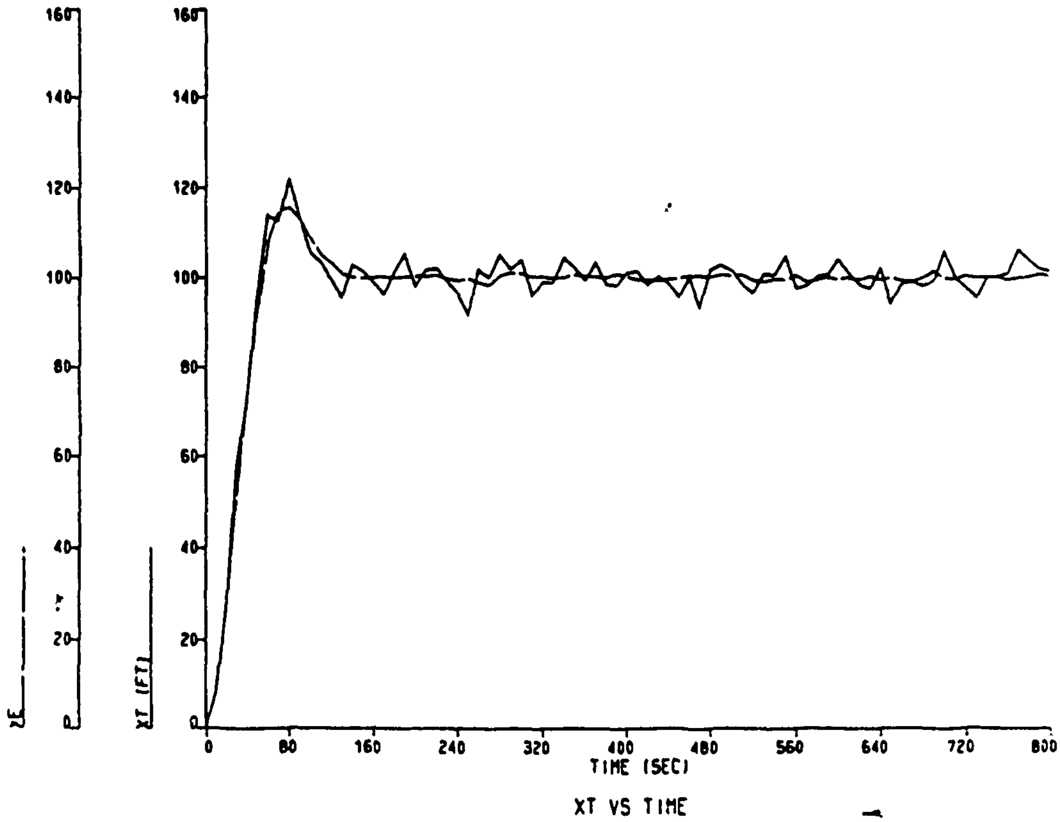

Figure 6. **Response in Surge:** Sea state 0, No current, No wind. XT is measured surge position and XE is estimated surge position.

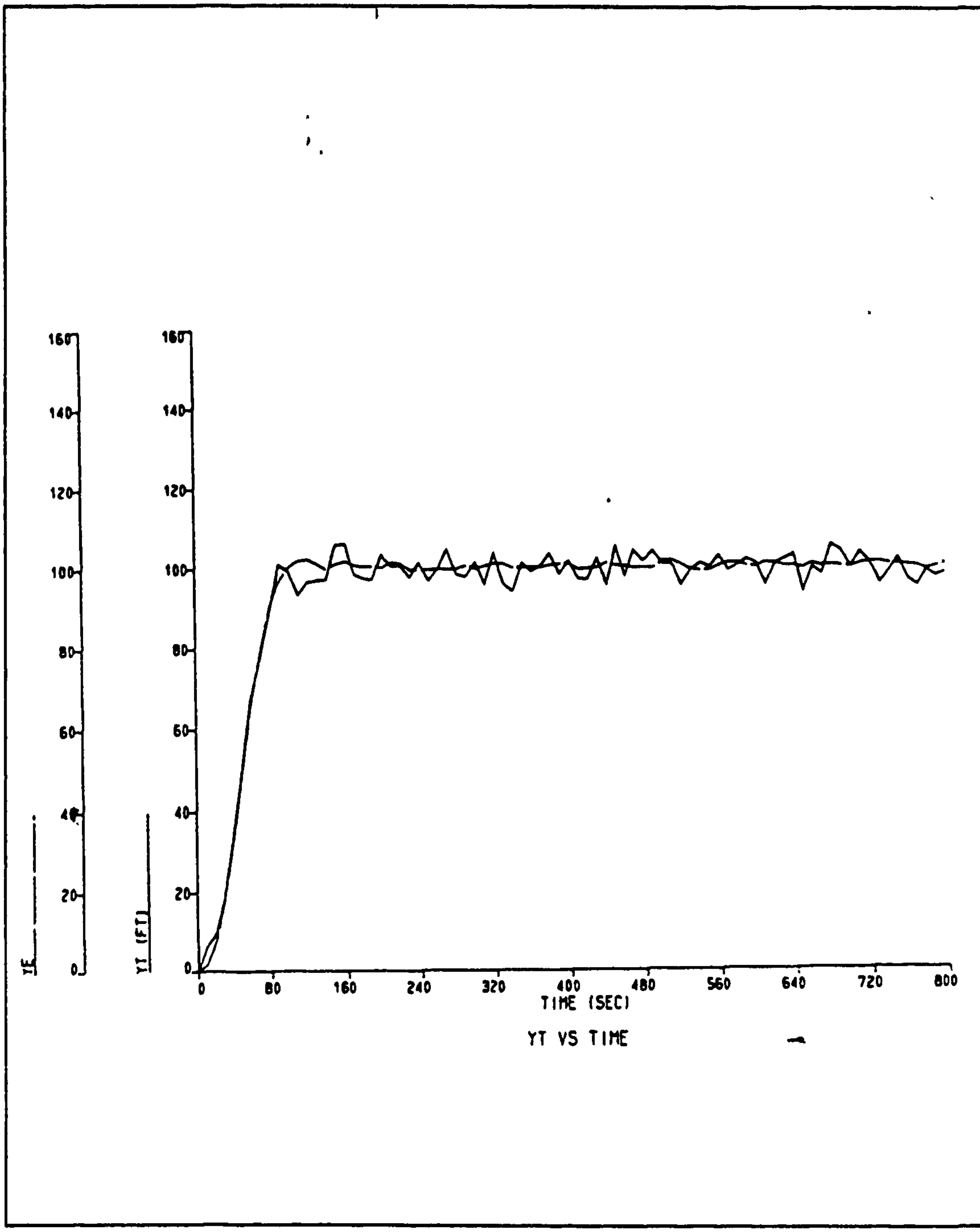

Figure 7. Response in Sway: Sea state 0, No current, No wind. YT is measured sway position and YE is estimated sway position.

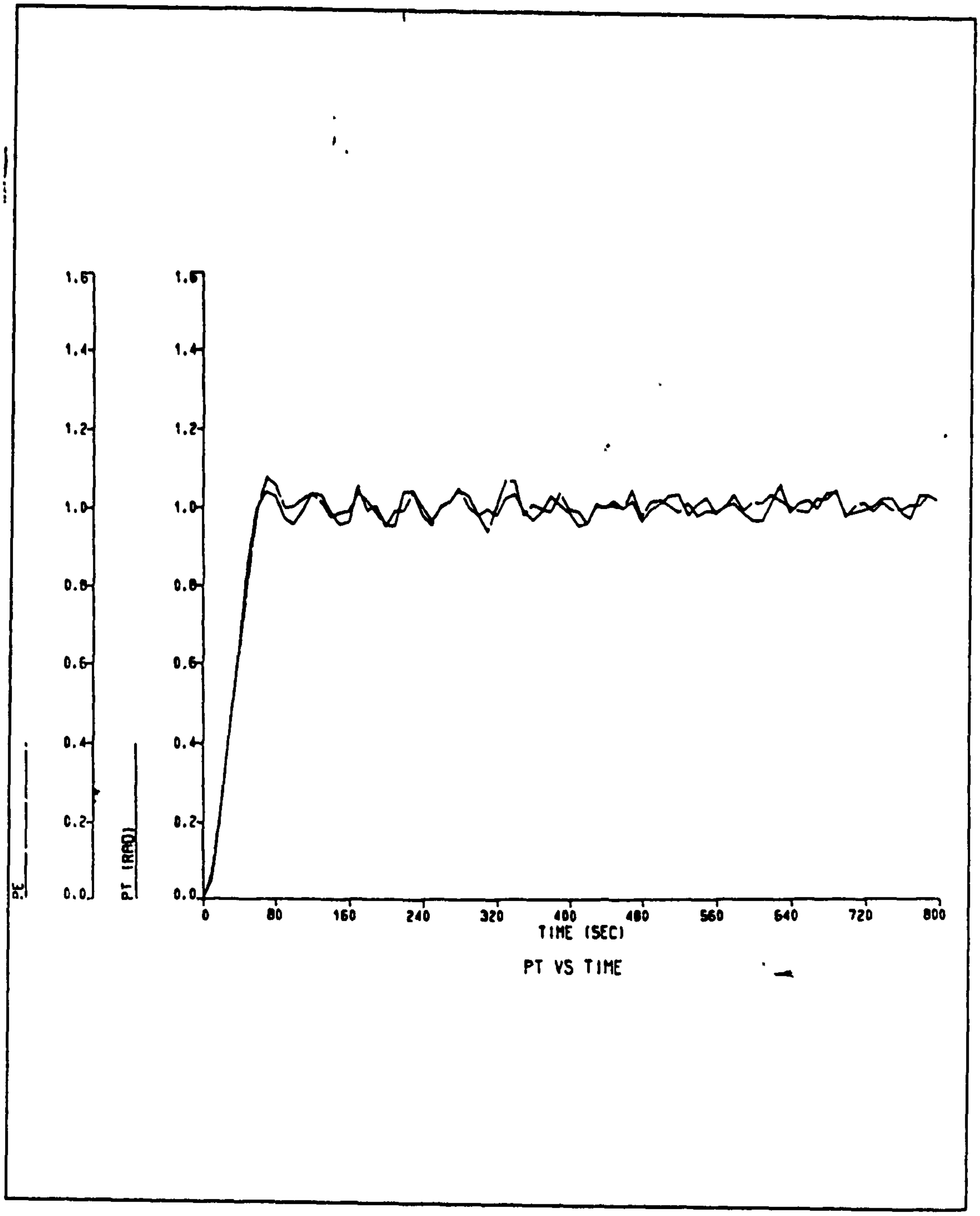

Figure 8. Response in Yaw: Sea state 0, No current, No wind. PT is measured yaw angle and PE is estimated yaw angle.

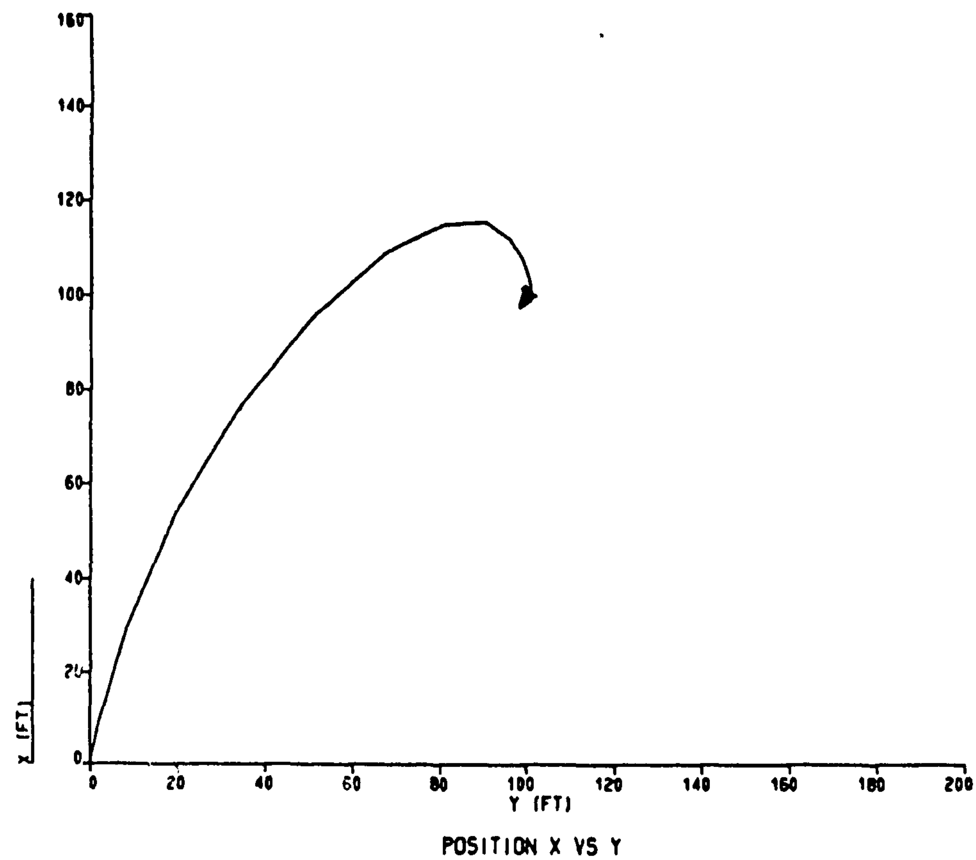

Figure 9. Position Plot: Sea state 0, No wind, No current

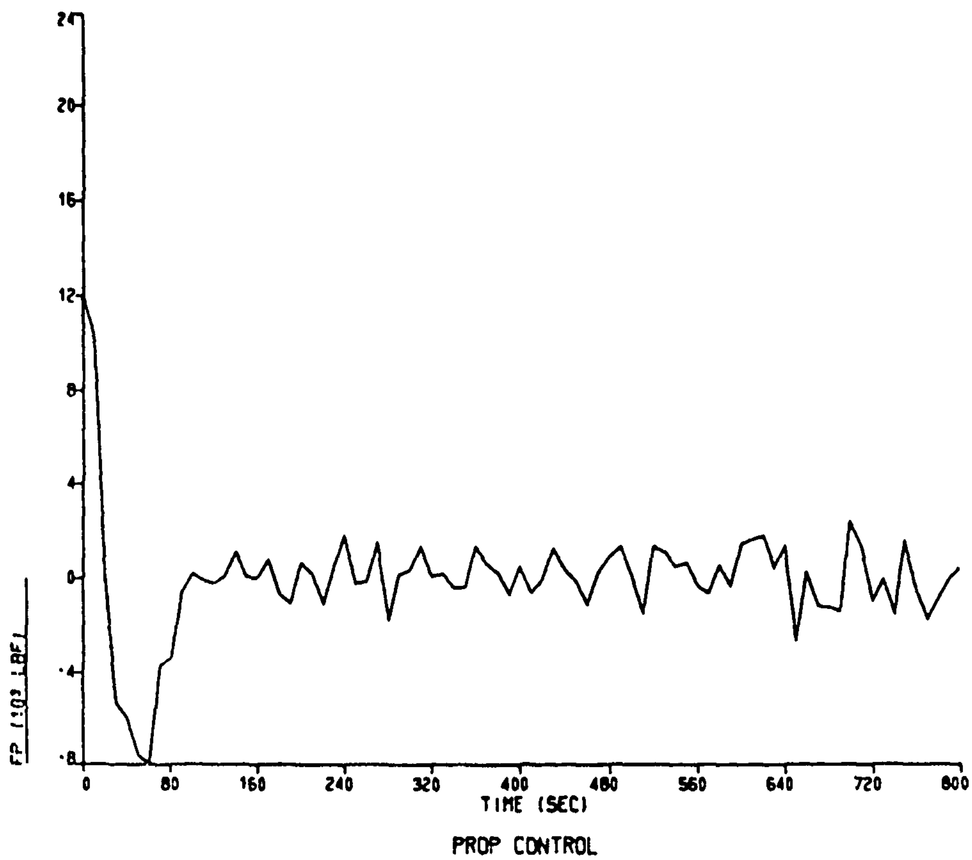

Figure 10. Main Propulsion Force: Sea state 0, No wind, No current

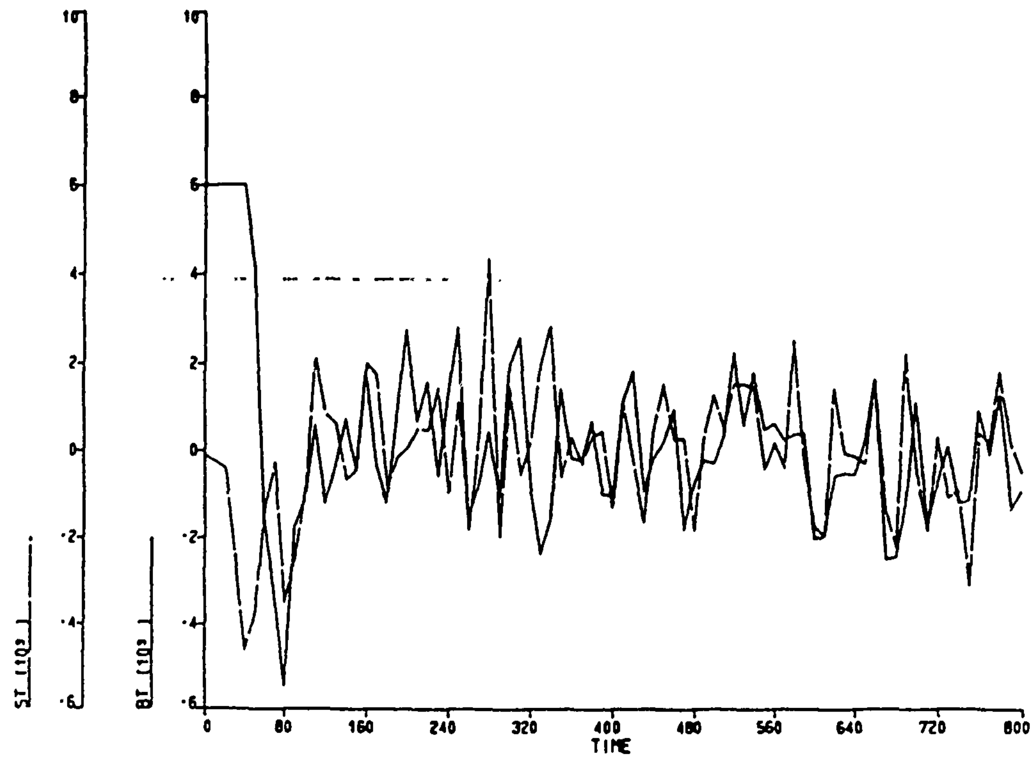

Figure 11. Bow and Stern Thruster Forces: Sea state 0, No wind, No current.

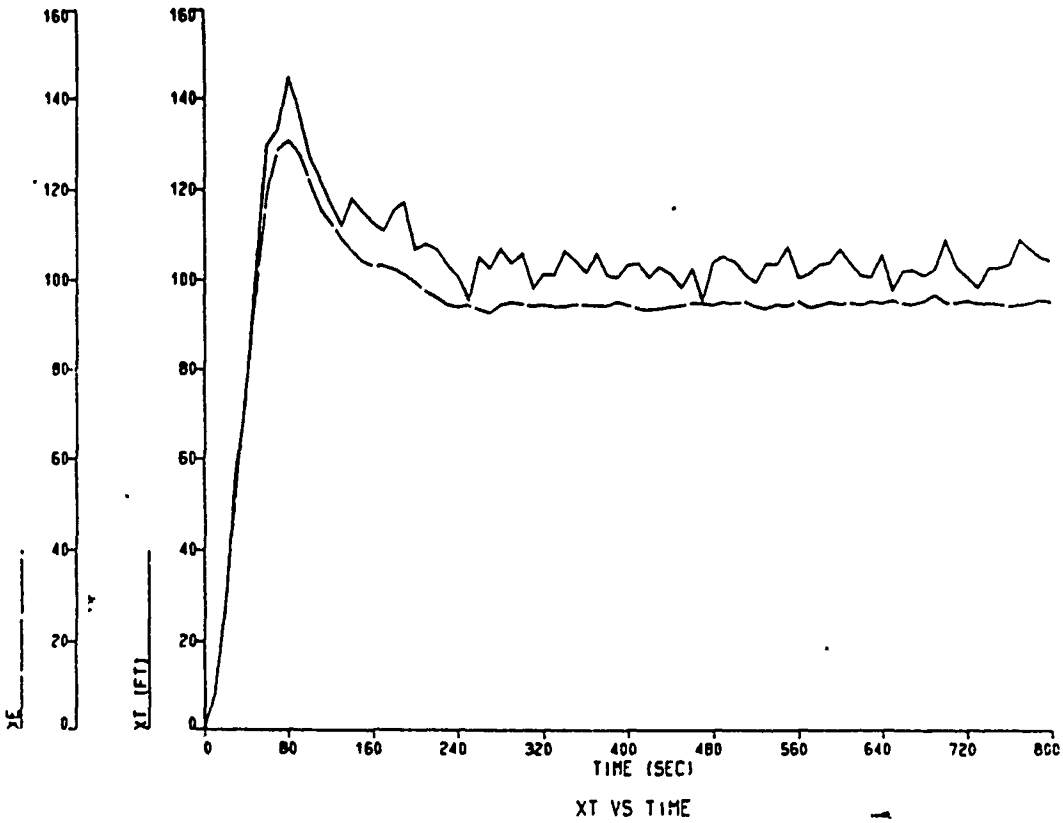

Figure 12. Surge Response: Sea state 0, No wind, Current = 3 fps. XT is measured surge position and XE is estimated surge position.

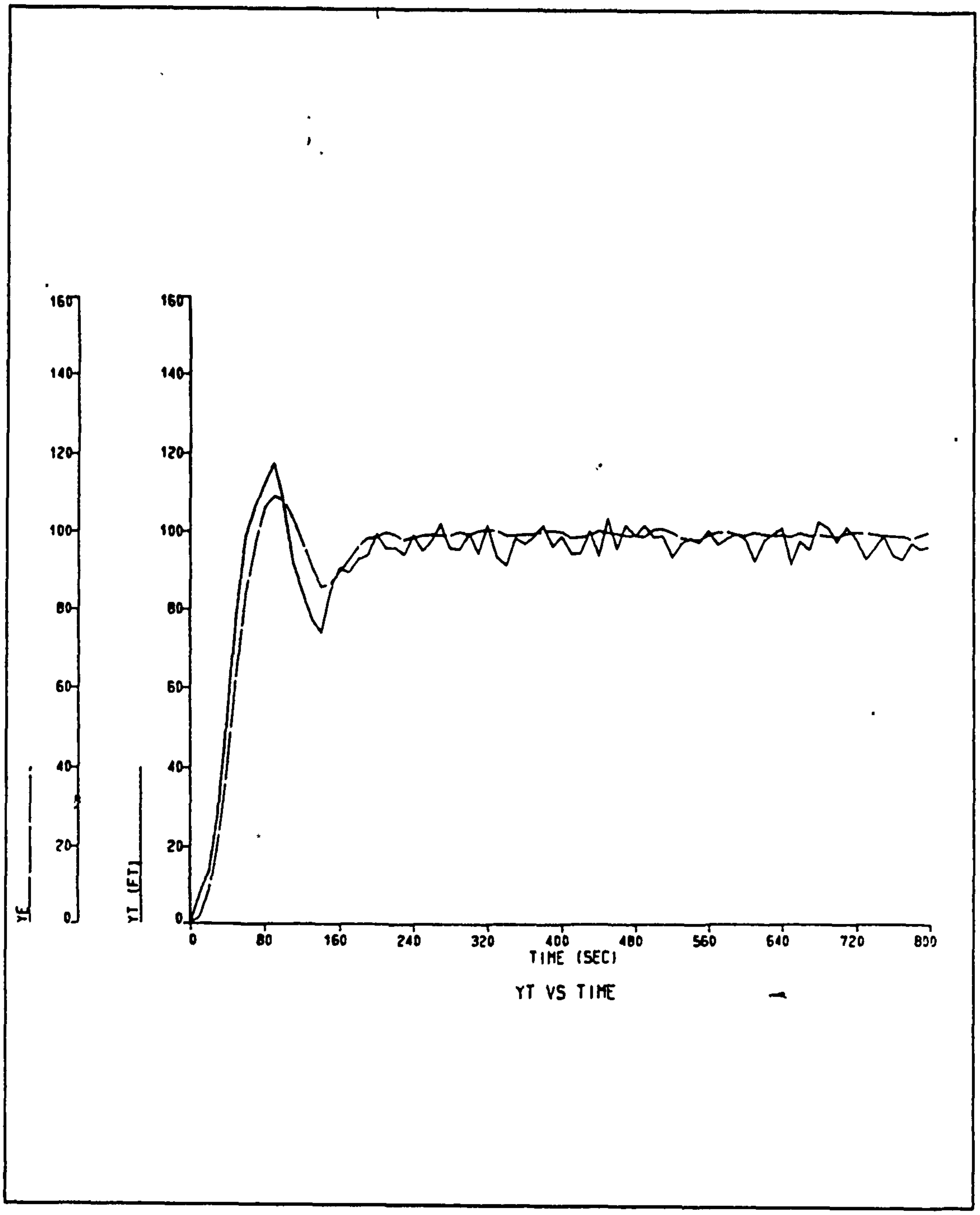

Figure 13. **Sway Response:** Sea state 0, No wind, Current = 3 fps. YT is measured sway position and YE is estimated sway position

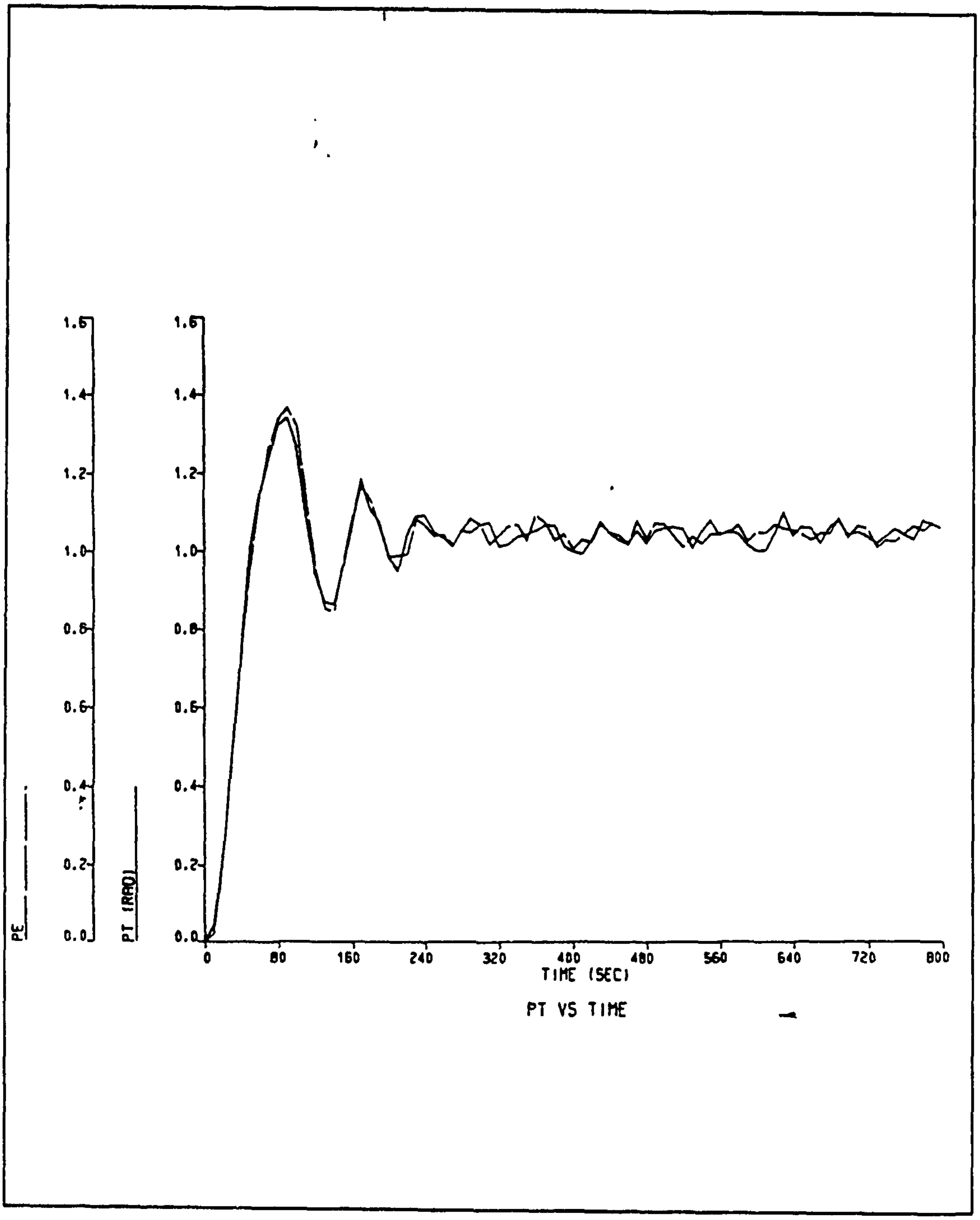

Figure 14. Yaw Response: Sea state 0, No wind, Current = 3 fps. PT is measured yaw angle and PE is estimated yaw angle.

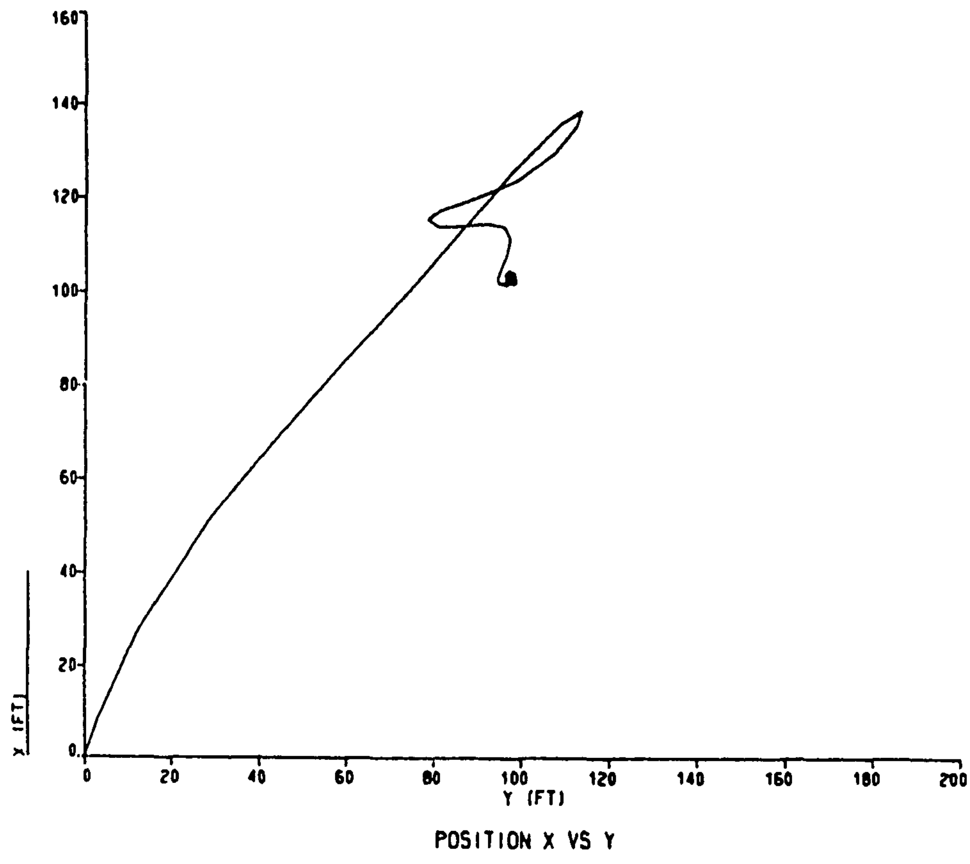

Figure 15. Position Plot: Sea state 0, No wind, Current = 3 fps

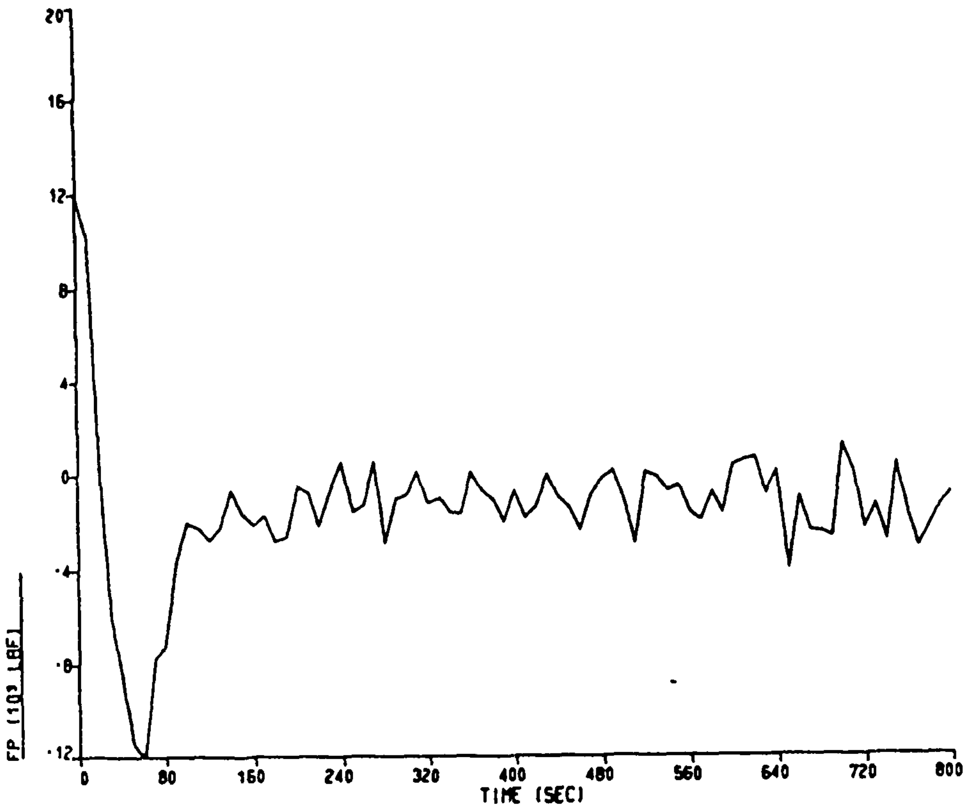

Figure 16. **Main Propulsion Force:** Sea state 0, No wind, Current = 3 fps

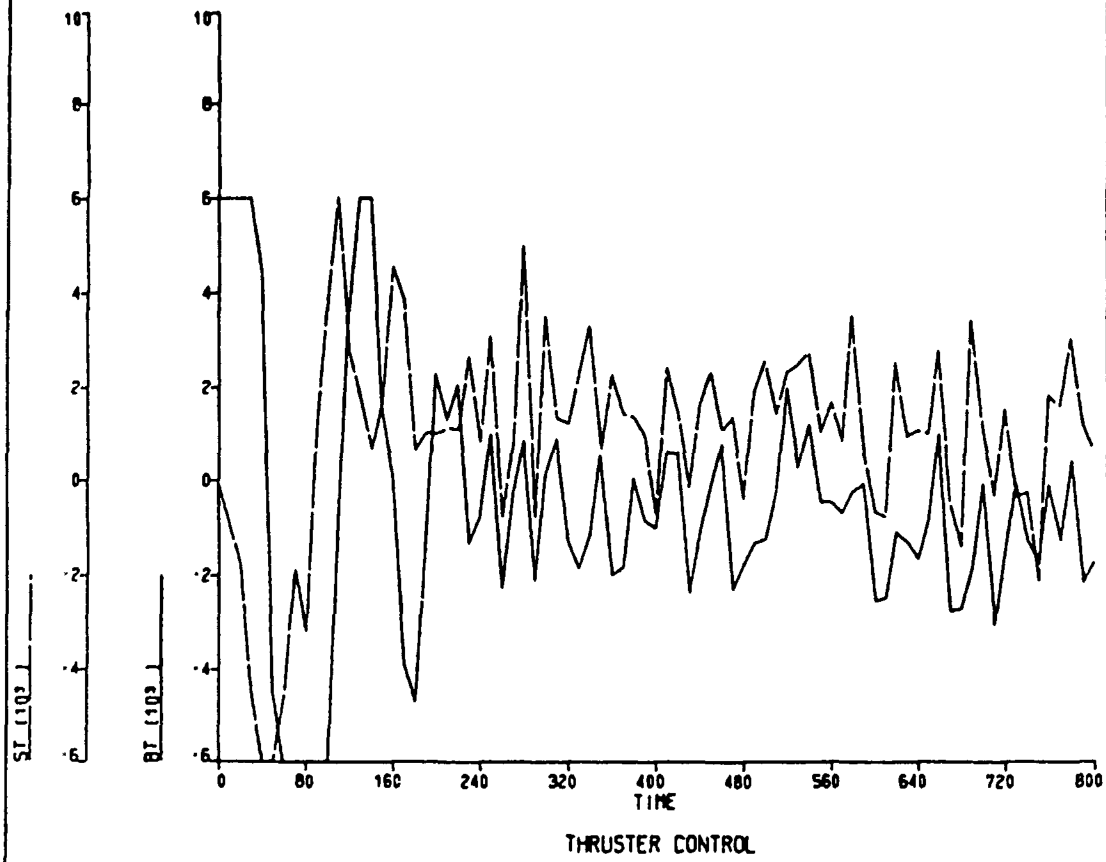

Figure 17. **Bow and Stern Thruster Forces :** Sea state 0, No wind, Current = 3 fps

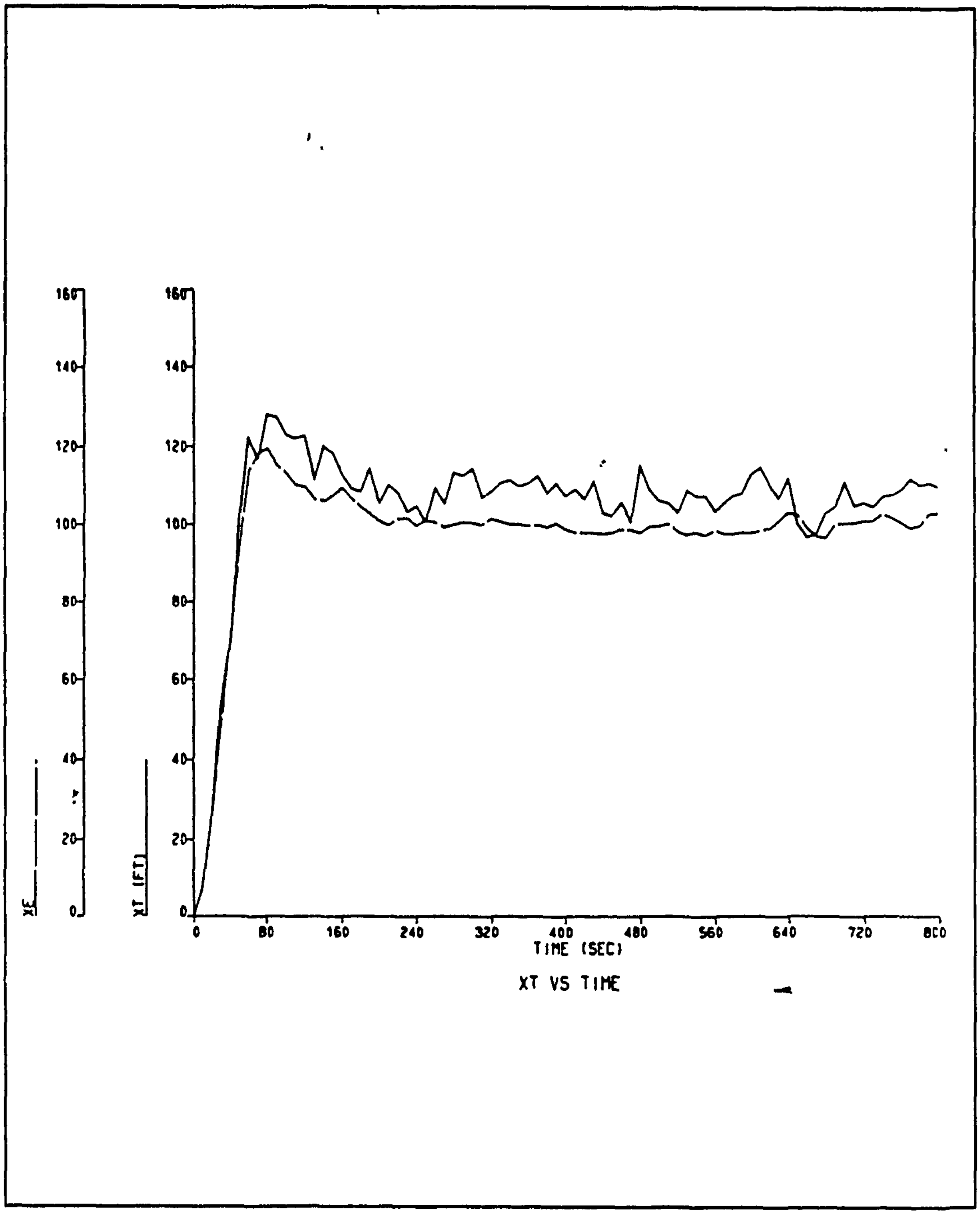

Figure 18. Surge Response: Sea state 5, Wind = 30 knots, Current = 3 fps. XT is measured surge position and XE is estimated surge position.

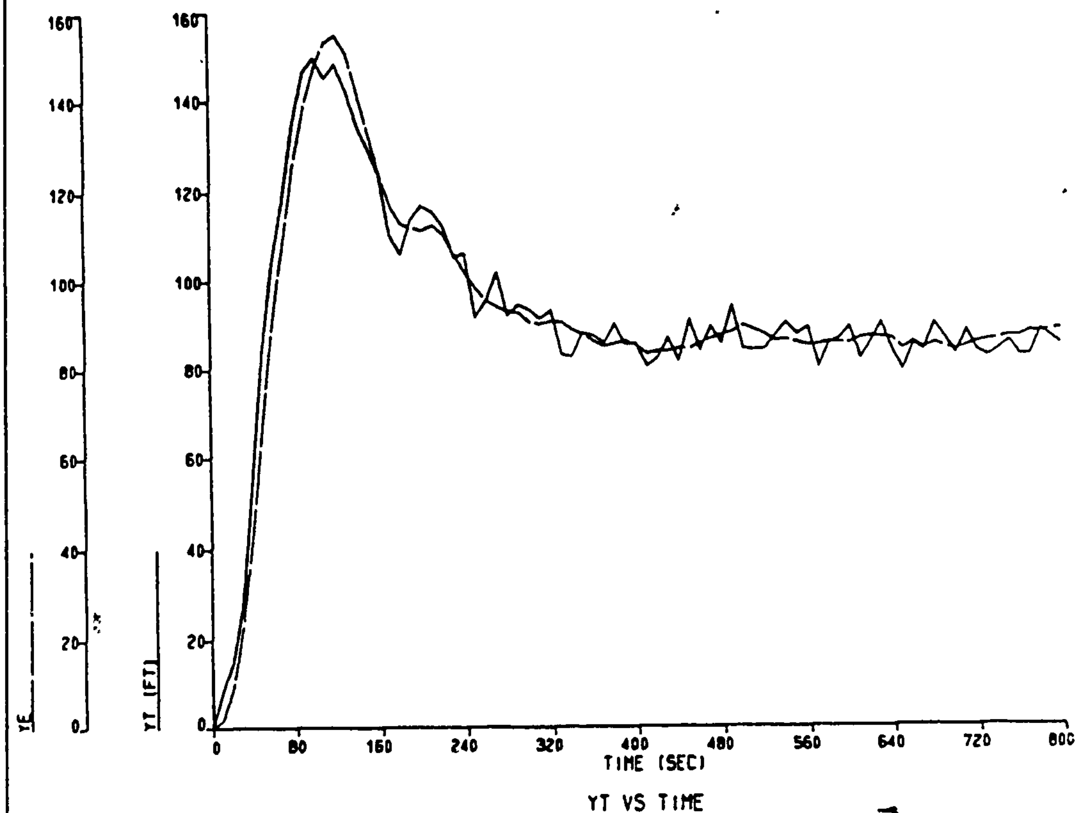

Figure 19. Sway Response: Sea state 5, Wind = 30 knots, Current = 3 fps. YT is measured sway position and YE is estimated sway position.

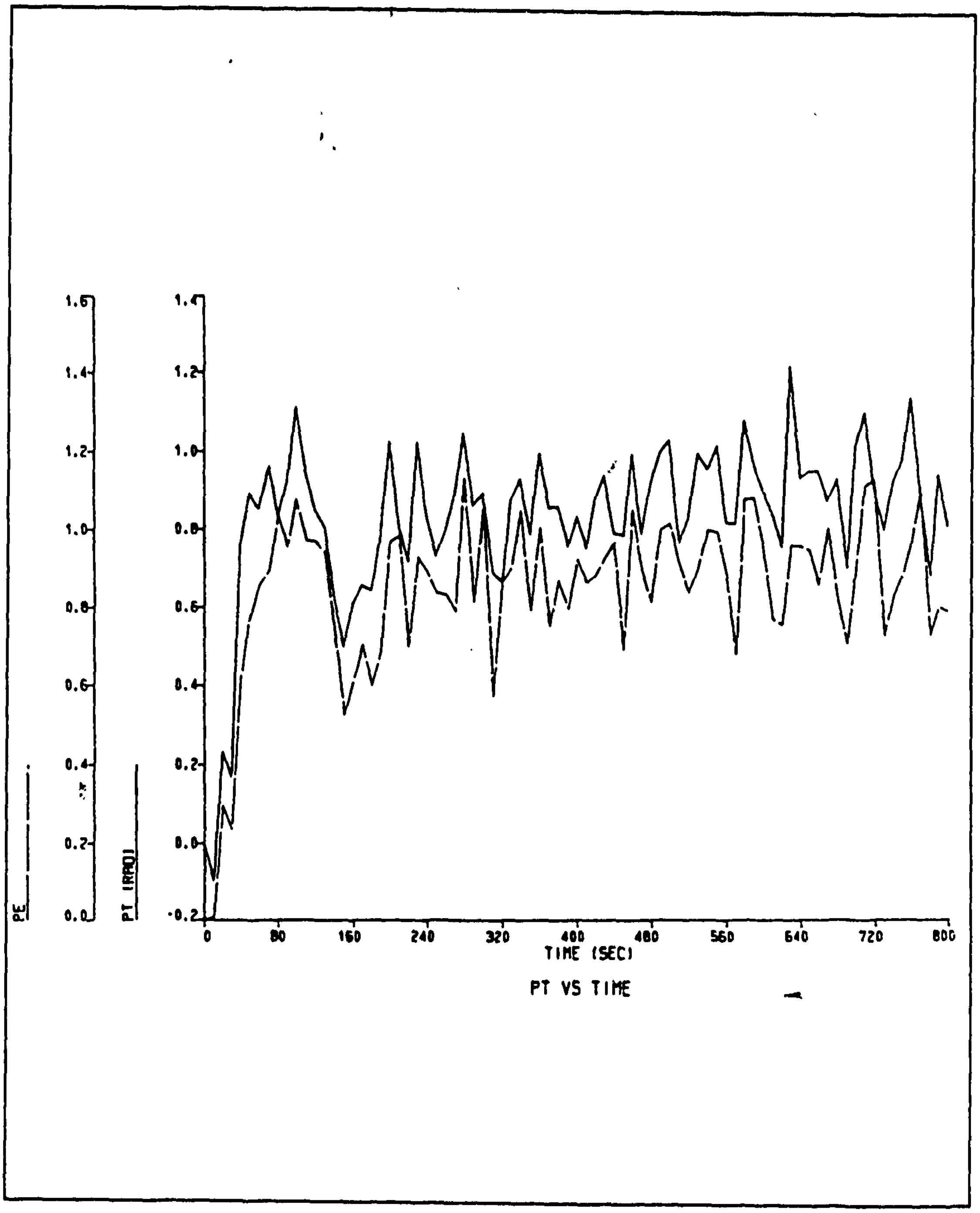

Figure 20. **Yaw Response:** Sea state 5, Wind = 30 knots, Current = 3 fps. PT is measured yaw angle and PE is estimated yaw angle.

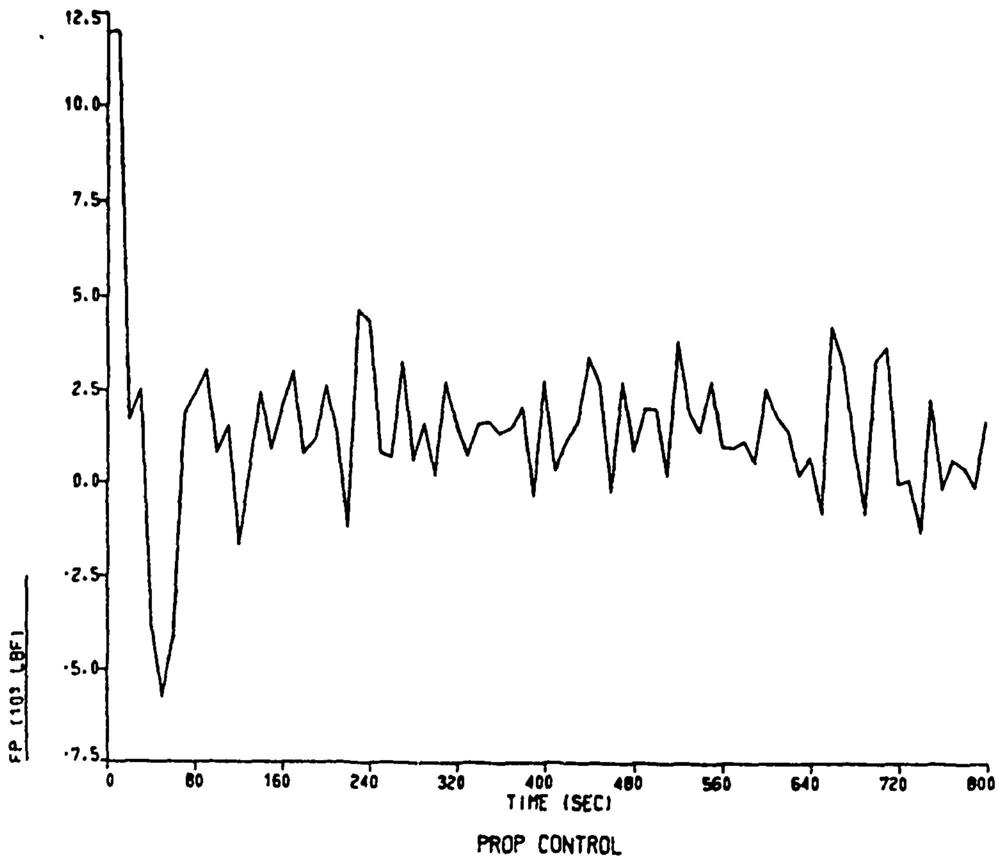

Figure 21. Main Propulsion Force: Sea state 5, Wind = 30 knots, Current = 3 fps

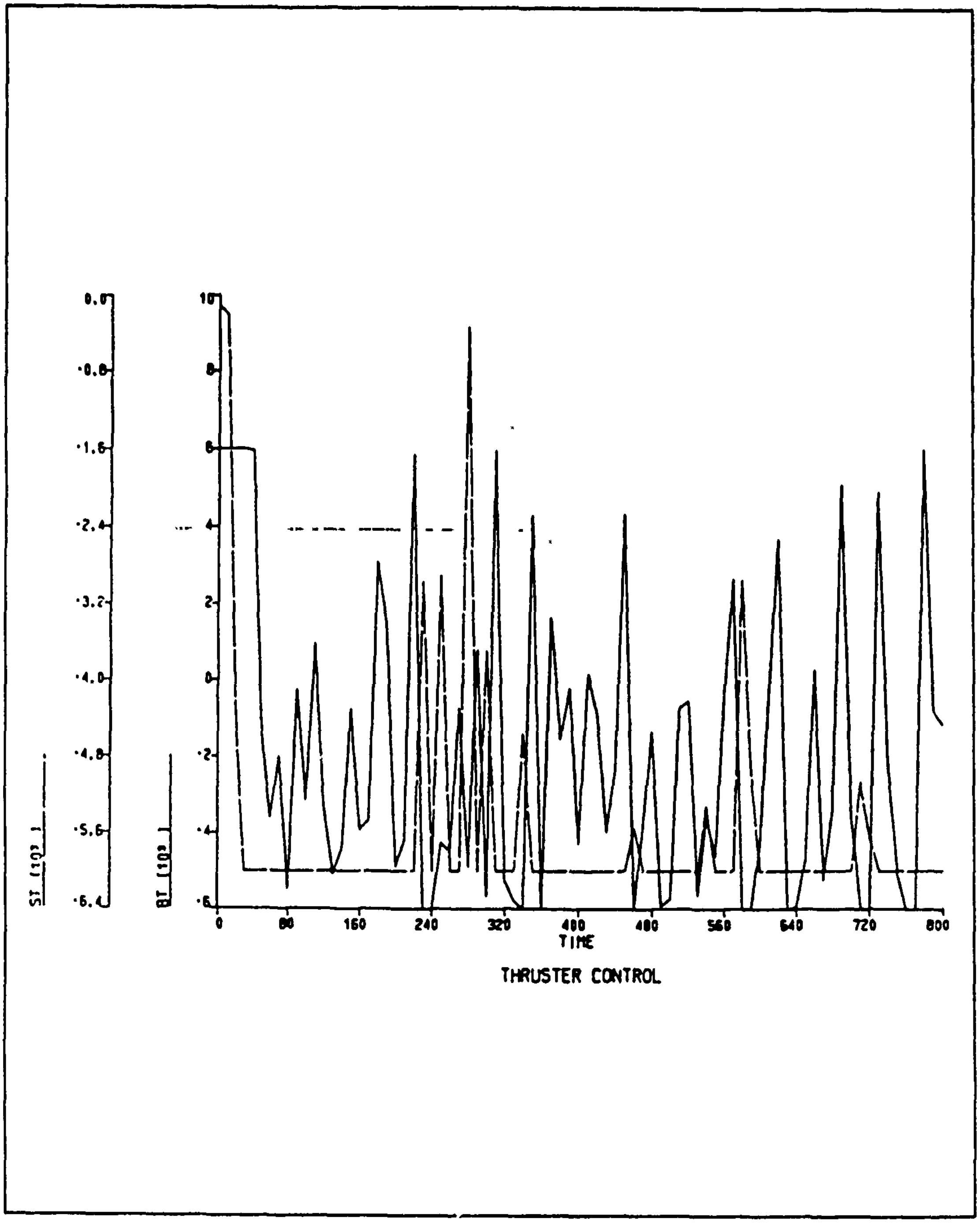

Figure 22. Bow and Stern Thruster Forces: Sea state 5, Wind = 30 knots, Current = 3 fps

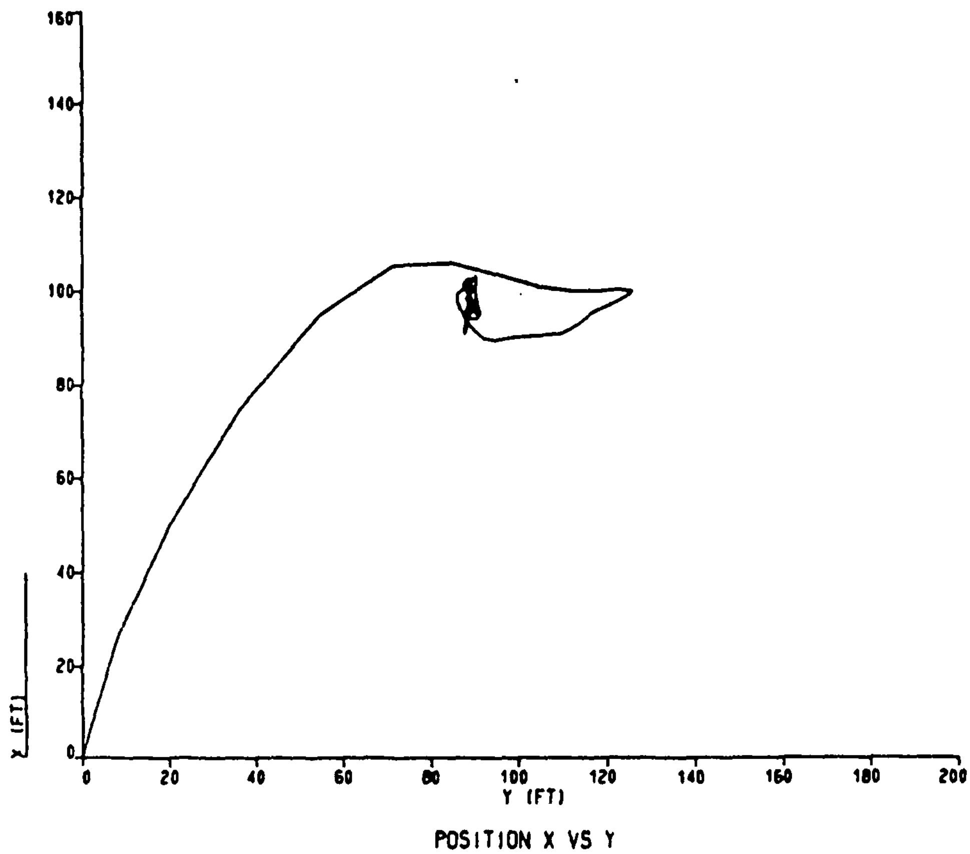

Figure 23. Position Plot: Sea state 5, Wind = 30 knots, Current = 3 fps

VII. CONCLUSIONS

This computer-based dynamic positioning system is a viable alternative to manual position keeping methods in environmental conditions of up to sea state 5, current up to 1.5 knots, and wind up to 30 knots, particularly when precision requirements are deemed to be of greater importance than fuel cost. In order to meet the requirments for the new buoy tender fleet, bow and stern thrusters of 400 SHP should be installed. These will allow the DP system to maintain vessel position and heading in the environments specified. In addition, variable azimuth thrusters will provide enhanced control system performance over fixed tunnel thrusters.

APPENDIX A. STANDARD SHIP MOTION PROGRAM

The added mass and drag coefficients for the 180 foot WLB "IRIS" class buoy tender are dimensionalized forms of the values presented here.

```
180 Foot WLB ("USCG IRIS CLASS") 14 June 1989

                    TABLE OF SHIP PARTICULARS

SHIP CHARACTERISTICS -

   SHIP LENGTH (LPP)         170.00 FEET      LENGTH/BEAM              4.595
   BEAM AT MIDSHIPS           37.00 FEET      BEAM/DRAFT               3.083
   DRAFT AT MIDSHIPS          12.00 FEET      DRAFT/BEAM               0.324
   DISPLACEMENT (S.W.)       943.5 L. TONS    DISPL/(.01LPP)**3      192.049
   DESIGN SHIP SPEED          12.00 KNOTS     FROUDE NUMBER            0.274

VERTICAL LOCATIONS -

   C. OF GRAVITY (VCG)*        2.27 FEET      VCG/BEAM                 0.061
   C. OF GRAVITY (KG)**       14.27 FEET      KG/BEAM                  0.386
   METACENTRIC HT. (GM)        2.87 FEET      GM/BEAM                  0.078
   METACENTER (KM)**          17.14 FEET      KM/BEAM                  0.463
   C. OF BUOYANCY (KB)**       7.18 FEET      KB/BEAM                  0.194

LONGITUDINAL LOCATIONS*** -

   C. OF GRAVITY (LCG)        83.80 FEET      LCG/LENGTH               0.493
   C. OF BUOYANCY (LCB)       83.80 FEET      LCB/LENGTH               0.493
   C. OF FLOTATION (LCF)      84.39 FEET      LCF/LENGTH               0.500

MOTION CHARACTERISTICS -

   ROLL GYRADIUS              14.80 FEET      RG/BEAM                  0.400
   PITCH GYRADIUS             42.50 FEET      PG/LPP                   0.250
   YAW GYRADIUS               42.50 FEET      YG/LPP                   0.250
   ESTIMATED ROLL PERIOD      10.81 SECONDS   ROLL FREQ (RADIANS)      0.581

COMPUTED AREAS -

   WATERPLANE               4341.7 SQ. FEET   AWP/(LPP*BEAM)           0.690
   WETTED SURFACE, HULL     6225.4 SQ. FEET   WS/(2L*(2D+B))           0.553

HULL COEFFICIENTS -

   BLOCK (CB)                 0.437
   SECTION (CX)               0.775
   PRISMATIC (CP)             0.564

*  WATERLINE REFERENCE
** KEEL REFERENCE
***F.P. REFERENCE


180 Foot WLB ("USCG IRIS CLASS") 14 June 1989

              TABLE OF SHIP APPENDAGE PARTICULARS

SKEG CHARACTERISTICS -

   SKEG LENGTH ALONG KEEL (SET NO. 1)                    31.50 FEET
   SKEG HEIGHT (SET NO. 1)                               10.00 FEET
   TOTAL WETTED SURFACE AREA (SKEG SET NO. 1)              314 SQ. FEET
                           AREA / (LPP * DRAFT)          0.077

RUDDER CHARACTERISTICS -

   RUDDER ROOT CHORD LENGTH (SET NO. 1)                   1.75 FEET
   RUDDER TIP CHORD LENGTH  (SET NO. 1)                   1.75 FEET
   RUDDER MEAN SPAN (SET NO. 1)                           9.25 FEET
   TOTAL WETTED SURFACE AREA (RUDDER SET NO. 1)             32 SQ. FEET
                           AREA / (LPP * DRAFT)          0.008

NOTE:  IF A "SET" REPRESENTS A PAIR OF APPENDAGES (E.G., BILGE KEELS),
       THEN THE WETTED SURFACE IS COMPUTED FOR THE TOTAL AREA OF BOTH
       APPENDAGES.
```

Figure 24. SSMP Vessel Particulars

180 Foot WLB ('USCG IRIS CLASS') 14 June 1989

ZERO-SPEED ADDED-MASS AND DAMPING COEFFICIENTS

NON-DIMENSIONAL ADDED-MASS

SIGMA	A(1,1)	A(2,2)	A(3,3)	A(4,4)	A(5,5)	A(6,6)	A(2,4)	A(2,6)	A(3,5)	A(4,6)
0.115	1.9732E-01	1.1573E+00	8.0894E+00	1.0452E-03	3.3621E-01	9.1004E-02	-1.0407E-02	-6.3050E-02	1.1411E-01	-9.4395E-04
0.230	1.5618E-01	1.1650E+00	6.2310E+00	1.0508E-03	2.6499E-01	9.2026E-02	-1.0515E-02	-6.4827E-02	9.4815E-02	-9.8087E-04
0.575	1.0107E-01	1.2083E+00	3.8079E+00	1.0834E-03	1.6945E-01	9.6681E-02	-1.0432E-02	-7.1685E-02	6.6327E-02	-1.1291E-03
1.149	6.2212E-02	1.2765E+00	2.2030E+00	1.1280E-03	1.0242E-01	9.5256E-02	-1.3771E-02	-5.7946E-02	4.4573E-02	-7.3999E-04
1.724	4.3444E-02	1.2771E+00	1.5031E+00	1.1236E-03	7.0869E-02	8.2406E-02	-1.9109E-02	-2.0506E-02	3.3751E-02	1.8101E-04
2.299	3.2912E-02	1.1261E+00	1.1624E+00	1.0211E-03	5.3997E-02	7.1911E-02	-1.8051E-02	-8.5201E-03	2.7554E-02	3.8292E-04
3.448	2.3018E-02	6.2246E-01	9.4342E-01	6.7210E-04	3.9771E-02	4.6188E-02	-7.9984E-03	-1.3006E-02	2.0984E-02	9.4535E-05
4.597	2.0051E-02	4.2395E-01	9.6360E-01	5.2835E-04	3.6631E-02	3.4815E-02	-3.2801E-03	-1.7167E-02	1.7556E-02	-1.1298E-04
11.493	2.5764E-02	3.5899E-01	1.2790E+00	4.2433E-04	4.6963E-02	3.3490E-02	7.9614E-04	-1.5519E-02	1.7945E-02	-5.1690E-04
22.987	2.7342E-02	4.8778E-01	1.3360E+00	5.2758E-04	4.8373E-02	3.6855E-02	-2.6781E-03	-1.4982E-02	1.3429E-02	-3.5244E-04

NON-DIMENSIONAL DAMPING

SIGMA	B(1,1)	B(2,2)	B(3,3)	B(4,4)	B(5,5)	B(6,6)	B(2,4)	B(2,6)	B(3,5)	B(4,6)
0.115	1.0372E-02	1.1336E-04	4.6941E-01	9.6772E-08	1.7942E-02	2.1510E-05	4.3223E-06	-4.2344E-05	4.7107E-03	-1.0545E-06
0.230	2.0395E-02	9.5703E-04	9.0274E-01	7.1915E-07	3.5227E-02	1.7967E-04	3.5200E-05	-3.4449E-04	9.9171E-03	-8.2700E-06
0.575	4.6868E-02	1.9443E-02	1.9772E+00	1.4961E-05	8.0504E-02	3.4392E-03	4.0617E-04	-6.6028E-03	2.4943E-02	-1.5630E-04
1.149	7.8035E-02	2.0626E-01	3.0659E+00	1.5784E-04	1.3197E-01	2.9894E-02	3.6230E-03	-5.3868E-02	4.4090E-02	-1.2421E-03
1.724	9.6369E-02	5.7047E-01	3.5258E+00	4.8384E-04	1.5964E-01	6.1108E-02	-2.1175E-03	-7.5759E-02	5.6731E-02	-1.5183E-03
2.299	1.0569E-01	1.4664E+00	3.5851E+00	1.0474E-03	1.7111E-01	9.6879E-02	-2.0152E-02	-5.7548E-02	6.5182E-02	-7.2587E-04
3.448	1.0675E-01	2.2967E+00	3.0750E+00	1.4708E-03	1.6576E-01	1.4111E-01	-4.2488E-02	-2.3500E-02	7.5235E-02	-5.3175E-04
4.597	9.5333E-02	2.1015E+00	2.3510E+00	1.6144E-03	1.4440E-01	1.3216E-01	-4.3076E-02	-1.4500E-02	7.9696E-02	9.1895E-04
11.493	2.8055E-02	1.1265E+00	3.7909E-01	9.9480E-04	4.1782E-02	3.7840E-02	-3.0407E-02	6.9328E-03	2.7671E-04	-1.3568E-04
22.987	7.7987E-03	-1.6550E-01	1.4771E-01	-6.9481E-05	1.6948E-02	-2.5638E-02	2.5396E-03	7.0243E-02	3.9683E-02	-7.2881E-04

(SIGMA IS NON-DIMENSIONAL FREQUENCY)

Figure 25. SSMP Added Mass and Damping Coefficients

APPENDIX B. IODE SIMULATIONS

The following are printouts from IODE programs. IODE (Interactive Ordinary Differential Equations) is an interactive software package that runs on the VM/CMS mainframe. IODE interrogates the user about the system of differential equations and provides the solution in tabular and/or graphical form.

The first program of this appendix is a model of the low frequency vessel in surge. The vessel is modeled at full propulsive force, with no environmental disturbances. Using the SMP value for vessel effective mass and the derived value for the drag coefficient, the vessel is simulated in the open loop configuration and velocity plotted against time in Figure 26 on page 50 The IODE program listing is:

```
VARIABLES & INITIAL CONDITIONS:
X = .0
XD = .0
T = .0

CONSTANTS:
MX = 71920.00000
NX = .0
DX = 169.0000000
FWX = .0
UC = .0
U = 20250.00000

SPECIAL FUNCTIONS:
CC = XD-UC

DERIVATIVES:
D(X /D(T ) = =
    XD
D(XD /D(T ) = =
    NX+(U+FWX-DX*ABS(CC)*CC)/MX

OUTPUTS:
   TITLE: SURGE NO FEEDBACK
   NO TABULATION
   PLOT: X       XD
      AGAINST: T
   PLOT: XD
      AGAINST: T      AT INTERVAL    .2000000000
```

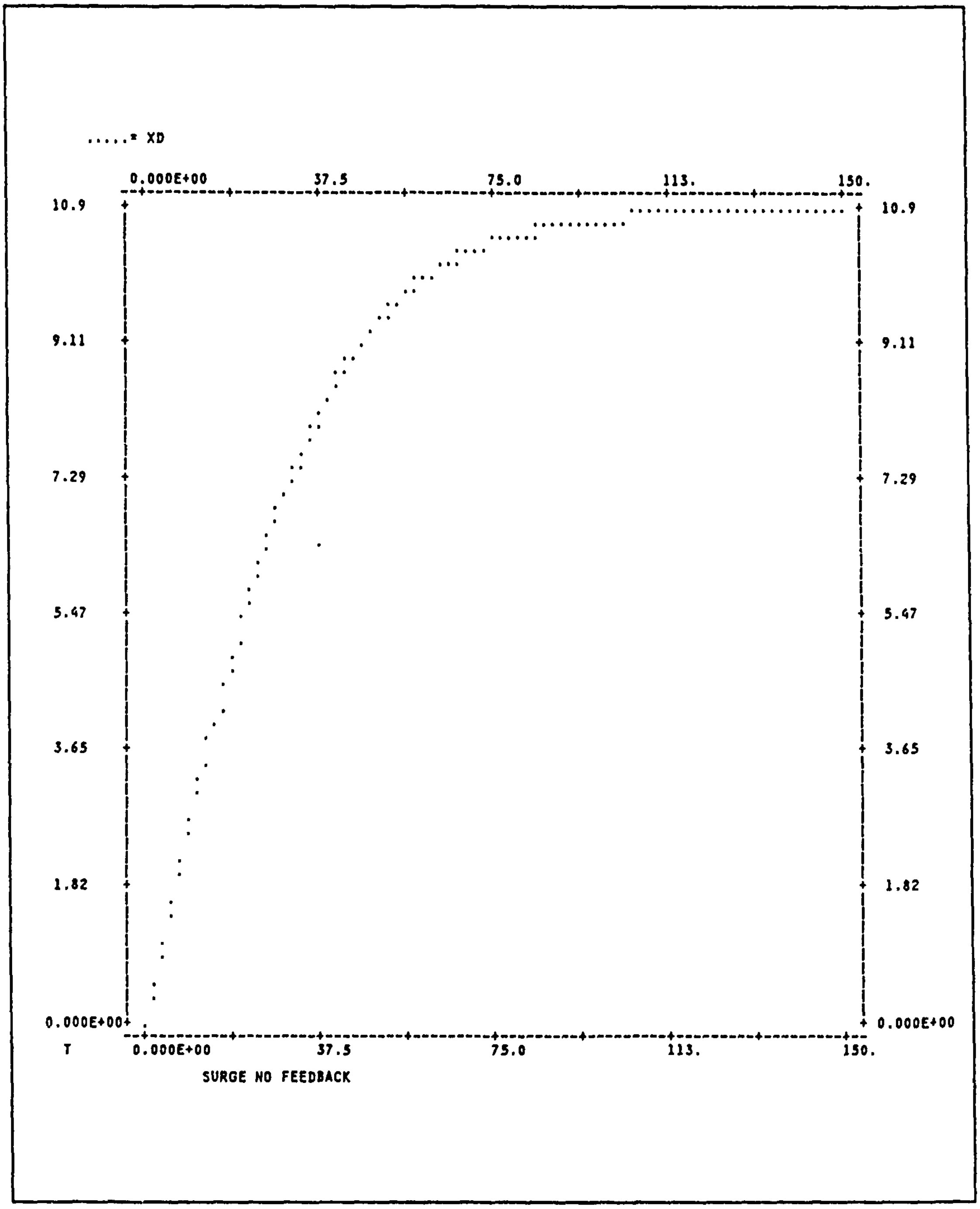

Figure 26. Surge Motion with No Feedback

As in the first simulation, the low frequency sway of the vessel is modeled in the open loop and velocity plotted against time in Figure 27 on page 51. The IODE program for sway is:

```
VARIABLES & INITIAL CONDITIONS:
Y = .0
YD = .0
T = .0

CONSTANTS:
MY = 147615.0000
DY = 869.0000000
FWY = .0
VC = .0
FT = 12000.00000
NY = .0

SPECIAL FUNCTIONS:
CC = YD-VC

DERIVATIVES:
D(Y /D(T ) = =
    YD
D(YD /D(T ) = =
    NY+((FT+FWY-DY*ABS(CC)*CC)/MY)

OUTPUTS:
   TITLE: SWAY NO FEEDBACK
   NO TABULATION
   PLOT: YD
     AGAINST: T      AT INTERVAL    .2000000000

END CALCULATION WHEN T .GE. 150.000
```

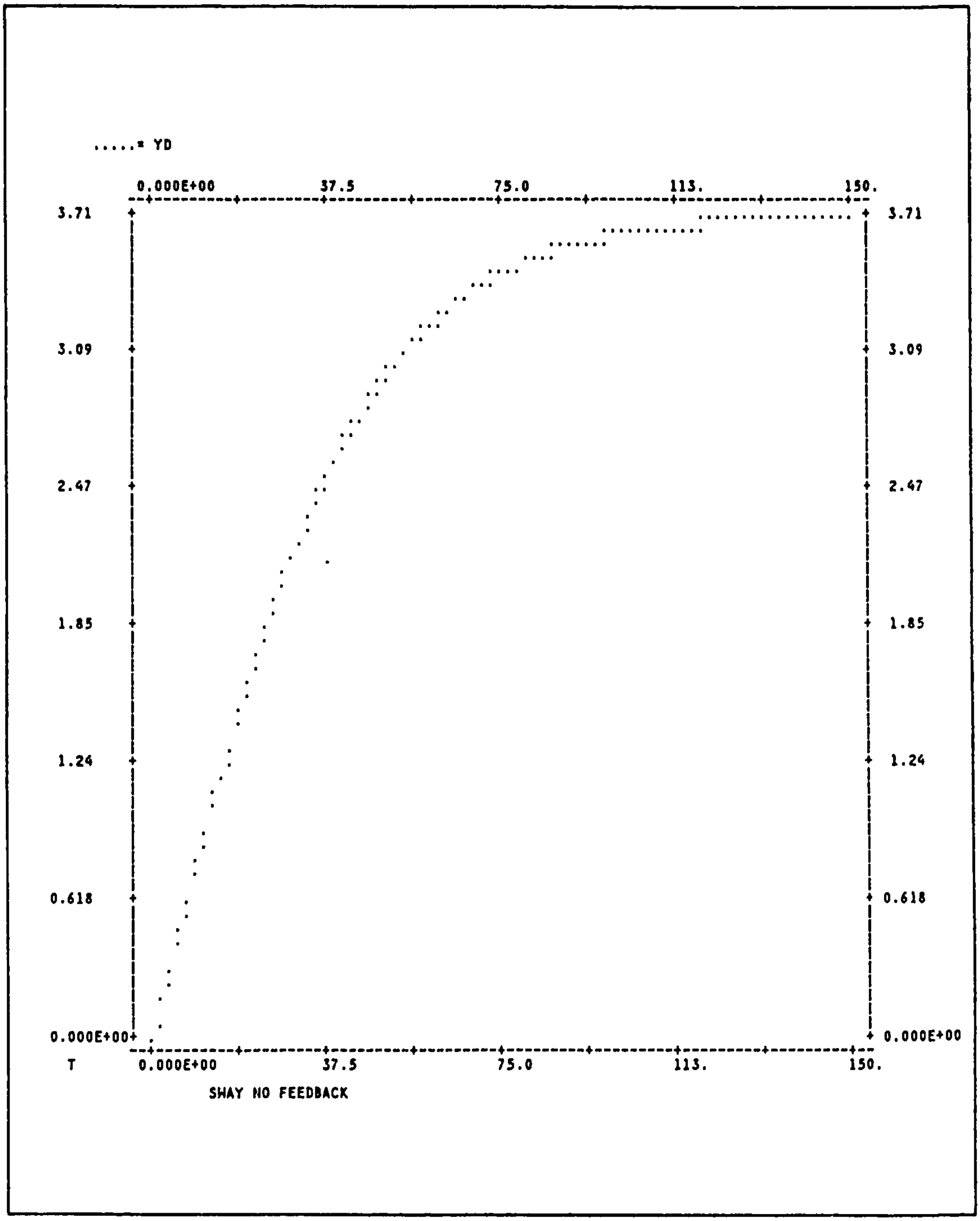

Figure 27. Sway Motion with No Feedback

Finally, the yaw motion of the low frequency model is simulated in the open loop mode and heading angle rate plotted against time in Figure 28.

```
VARIABLES & INITIAL CONDITIONS:
P = .0
PD = .0
T = .0

CONSTANTS:
MP = 267000000.0
DP = 1170000000.
NP = .0
MW = .0
MC = .0
MT = 954000.0000
DUM = .0

DERIVATIVES:
D(P /D(T ) = =
    PD
D(PD /D(T ) = =
    NP+(MT+MW+MC-DP*ABS(PD)*PD)/MP

OUTPUTS:
   TITLE: PSI DOT
   NO TABULATION
   PLOT: PD
      AGAINST: T      AT INTERVAL    .2000000000

END CALCULATION WHEN T .GE. 150.000
```

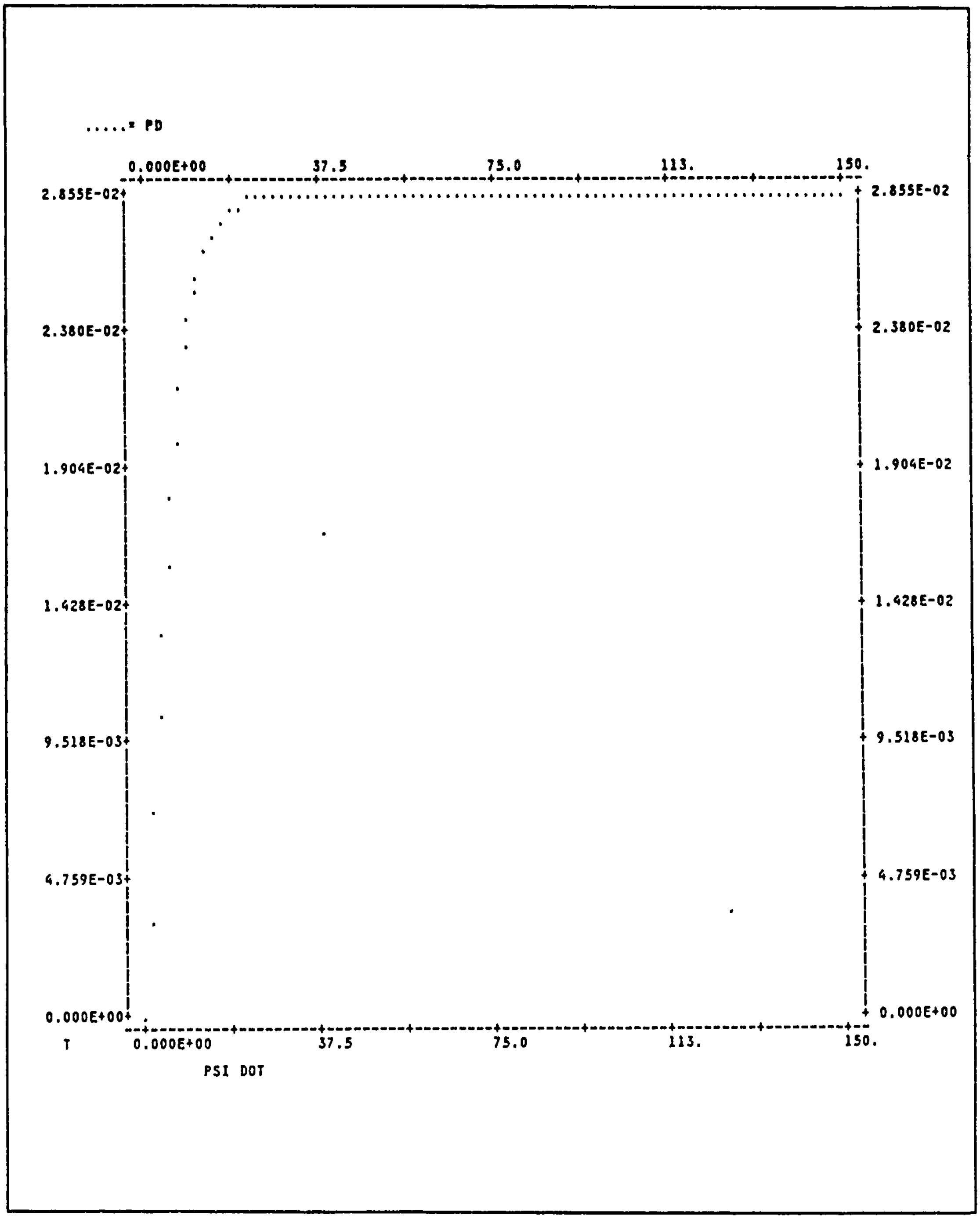

Figure 28. Yaw Motion with No Feedback

APPENDIX C. PROGRAM LISTING

The following is a listing of the DSL program which simulates the vessel, its environment, and the dynamic positioning control system. Comments are included throughout to augment the explanations provided in the body of the thesis.

```
*DEVELOPED BY W.R. CAIRNS, LCDR, USCG FOR THESIS RESEARCH:
*"DESIGN AND SIMULATION OF A DYNAMIC POSITIONING SYSTEM FOR A U.S.
*COAST GUARD BUOY TENDER"
TITLE: DPSIM5
*THIS PROGRAM SIMULATES A WLB "IRIS" CLASS USCG BUOY TENDER SUBJECT TO
*WIND, CURRENT, AND WAVE FORCES AND CONTROLLED BY A DYNAMIC POSITIONING
*SYSTEM
*THE PROGRAM PARAMETERS (PARAM) ARE DEFINED AS:
* F1,F2,F3 ARE THE VESSEL EFFECTIVE WIND AREAS IN SURGE,SWAY, AND YAW
* A1,A2 ARE THE VESSEL WIND VELOCITY AND DIRECTION FORCE COEFFICIENTS
* RX,RY,RP ARE THE REFERENCE POSITIONS IN SURGE,SWAY AND YAW
PARAM F1=2.294,F2=11.16,F3=474.3,...
      A1=0.001,A2=0.001,...
      W=00.8,...
      IWVS=30.0,...
      IWDS=0.0,...
      XCI=0.0,...
      YCI=0.0,...
      PCI=0.0,...
      RX=100.0,...
      RY=100.0,...
      RP=1.00
*THE CONSTANTS (CONST) ARE DEFINED:
* XO,XDO INITIAL CONDITIONS FOR SURGE VELOCITY AND ACCELERATION
* YO,YDO INITIAL CONDITIONS FOR SWAY VELOCITY AND ACCELERATION
* PO,PDO INITIAL CONDITIONS FOR YAW VELOCITY AND ACCELERATION
* MX,DX MASS AND DRAG COEFFICIENTS IN SURGE
* MY,DY MASS AND DRAG COEFFICIENTS IN SWAY
* MP,DP MASS AND DRAG COEFFICIENTS IN YAW
* NX,UX,SX SEED,MEAN,STD DEVIATION FOR LF PLANT NOISE IN SURGE
* NY,UY,SY SEED,MEAN,STD DEVIATION FOR LF PLANT NOISE IN SWAY
* NP,UP,SP SEED,MEAN,STD DEVIATION FOR LF PLANT NOISE IN YAW
* HNX,HUX,HSX SEED,MEAN,STD DEVIATION FOR HF PLANT NOISE IN SURGE
* HNY,HUY,HSY SEED,MEAN,STD DEVIATION FOR HF PLANT NOISE IN SWAY
* HNP,HUP,HSP SEED,MEAN,STD DEVIATION FOR HF PLANT NOISE IN YAW
* NWX,UWX,SWX SEED,MEAN,STD DEVIATION FOR HF FREQ NOISE IN SURGE
* NWY,UWY,SWY SEED,MEAN,STD DEVIATION FOR HF FREQ NOISE IN SWAY
* NWP,UWP,SWP SEED,MEAN,STD DEVIATION FOR HF FREQ NOISE IN YAW
* MNX,UMX,SMX SEED,MEAN,STD DEVIATION FOR LF MEAS NOISE IN SURGE
* MNY,UMY,SMY SEED,MEAN,STD DEVIATION FOR LF MEAS NOISE IN SWAY
* MNP,UMP,SMP SEED,MEAN,STD DEVIATION FOR LF MEAS NOISE IN YAW
* CNX,CUX,CSX SEED,MEAN,STD DEVIATION FOR CURRENT NOISE IN SURGE
* CNY,CUY,CSY SEED,MEAN,STD DEVIATION FOR CURRENT NOISE IN SWAY
* CNP,CUP,CSP SEED,MEAN,STD DEVIATION FOR CURRENT NOISE IN YAW
* NCX,MCX,SCX SEED,MEAN,STD DEVIATION FOR CURRENT NOISE IN SURGE(KALMAN)
```

```
* NCY,MCY,SCY SEED,MEAN,STD DEVIATION FOR CURRENT NOISE IN SWAY (KALMAN)
* NCP,MCP,SCP SEED,MEAN,STD DEVIATION FOR CURRENT NOISE IN YAW  (KALMAN)
* NWVS,UWVS,SWVS SEED,MEAN,SD FOR SLOW WIND VELOCITY NOISE
* NWVF,UWVF,SWVF SEED,MEAN,SD FOR FAST WIND VELOCITY NOISE
* NWDS,UWDS,SWDS SEED,MEAN,SD FOR SLOW WIND DIRECTION NOISE
* NWDF,UWDF,SWDF SEED,MEAN,SD FOR FAST WIND DIRECTION NOISE
* FPR,FPL PROPULSION LIMITER (+/-)
* BTR,BTL BOW THRUSTER LIMITER (+/-)
* STR,STL STERN THRUSTER LIMITER (+/-)
* EXD,EXU DEAD SPACE IN SURGE
* EYD,EYU DEAD SPACE IN SWAY
* EPD,EPU DEAD SPACE IN YAW
* RXD,RYD,RPD REFERENCE VELOCITIES IN SURGE, SWAY, YAW
* K VESSEL KALMAN FILTER GAINS SUBSCRIPTED ACCORDING TO MATRIX
* C CURRENT ESTIMATION FILTER GAINS SUBSCRIPTED ACCORDING TO MATRIX
* G OPTIMAL FEEDBACK GAINS SUBSCRIPTED ACCORDING TO MATRIX
CONST X0=0.0,XD0=0.0,...
      Y0=0.0,YD0=0.0,...
      P0=0.0,PD0=0.0,...
      MX=71920.0,DX=169.00000,...
      MY=147615.0,DY=869.0000,...
      MP=2.67D+08,DP=1.17D+09,...
      NX=19.0,UX=0.0,SX=0.0005,...
      NY=21.0,UY=0.0,SY=0.0005,...
      NP=23.0,UP=0.0,SP=0.00001,...
      HNX=19.0,HUX=0.0,HSX=3.0,...
      HNY=21.0,HUY=0.0,HSY=3.0,...
      HNP=23.0,HUP=0.0,HSP=0.175,...
      NWX=19.0,UWX=0.0,SWX=0.005,...
      NWY=21.0,UWY=0.0,SWY=0.005,...
      NWP=23.0,UWP=0.0,SWP=0.000175,...
      MNX=19.0,UMX=0.0,SMX=3.0000,...
      MNY=21.0,UMY=0.0,SMY=3.0000,...
      MNP=23.0,UMP=0.0,SMP=0.0175,...
      CNX=19.0,CUX=0.0,CSX=0.00050,...
      CNY=21.0,CUY=0.0,CSY=0.00050,...
      CNP=23.0,CUP=0.0,CSP=0.00001,...
      NCX=19.0,MCX=0.0,SCX=0.0005,...
      NCY=21.0,MCY=0.0,SCY=0.0005,...
      NCP=23.0,MCP=0.0,SCP=0.00001,...
      NWVS=19.0,UWVS=0.0,SWVS=0.0005,...
      NWVF=21.0,UWVF=0.0,SWVF=0.0005,...
      NWDS=23.0,UWDS=0.0,SWDS=0.00001,...
      NWDF=23.0,UWDF=0.0,SWDF=0.00001,...
      VNN=15.0,VNU=0.0,VNS=0.0005,...
      FPR=12000.0,FPL=-12000.0,...
      BTR=6000.0,BTL=-6000.0,...
      STR=6000.0,STL=-6000.0,...
      RXD=0.0,RYD=0.0,RPD=0.0,...
      K11=0.0669,K12=0.0,K13=0.0,...
      K21=0.0022,K22=0.0,K23=0.0,...
      K31=0.0,K32=0.0669,K33=0.0,...
      K41=0.0,K42=0.0022,K43=0.0,...
      K51=0.0,K52=0.0,K53=1.6069,...
      K61=0.0,K62=0.0,K63=1.2910,...
      C11=0.014,C12=0.0,C13=0.0,...
```

```
        C21=0.0044,C22=0.0,C23=0.0,...
        C31=0.0,C32=0.014,C33=0.0,...
        C41=0.0,C42=0.0044,C43=0.0,...
        C51=0.0,C52=0.0,C53=6.0000,...
        C61=0.0,C62=0.0,C63=18.200,...
        G11=193.0,G12=5701.00,G13=0.0,G14=0.0,G15=0.0,G16=0.0,...
        G21=0.0,G22=0.0,G23=150.0,G24=4434.0,G25=24962.0,G26=24962.0,...
        G31=0.0,G32=0.0,G33=193.0,G34=5701.0,G35=-19415.000,G36=-19415.00
*       G11=78.50,G12=9200.00,G13=0.0,G14=0.0,G15=0.0,G16=0.0,...
*       G21=0.0,G22=0.0,G23=42.00,G24=7200.0,G25=5854.0,G26=8200.0,...
*       G31=0.0,G32=0.0,G33=38.0,G34=6900.0,G35=-4553.000,G36=-7500.00
*       G11=77.46,G12=3335.50,G13=0.0,G14=0.0,G15=0.0,G16=0.0,...
*       G21=0.0,G22=0.0,G23=47.556,G24=2483.80,G25=249.62,G26=136.7,...
*       G31=0.0,G32=0.0,G33=61.14,G34=3193.40,G35=-194.150,G36=-106.34
DYNAMIC
*LOW FREQUENCY MODEL PLANT NOISE IN SURGE, SWAY, AND YAW
        NOIX=NORMAL(NX,UX,SX)
        NOIY=NORMAL(NY,UY,SY)
        NOIP=NORMAL(NP,UP,SP)
*HIGH FREQUENCY MODEL PLANT NOISE IN SURGE, SWAY, AND YAW
        HNOIX=NORMAL(HNX,HUX,HSX)
        HNOIY=NORMAL(HNY,HUY,HSY)
        HNOIP=NORMAL(HNP,HUP,HSP)
*MEASUREMENT NOISE IN SURGE, SWAY, AND YAW
        MNOIX=NORMAL(MNX,UMX,SMX)
        MNOIY=NORMAL(MNY,UMY,SMY)
        MNOIP=NORMAL(MNP,UMP,SMP)
*CURRENT NOISE IN SURGE, SWAY, AND YAW
        CXNOI=NORMAL(CNX,CUX,CSX)
        CYNOI=NORMAL(CNY,CUY,CSY)
        CPNOI=NORMAL(CNP,CUP,CSP)
*KALMAN FILTER CURRENT NOISE IN SURGE, SWAY, AND YAW
        KCX=NORMAL(NCX,MCX,SCX)
        KCY=NORMAL(NCY,MCY,SCY)
        KCP=NORMAL(NCP,MCP,SCP)
*WIND NOISE (SLOW/FAST VARYING)(VELOCITY AND DIRECTION)
        WVNS=NORMAL(NWVS,UWVS,SWVS)
        WVNF=NORMAL(NWVF,UWVF,SWVF)
        WDNS=NORMAL(NWDS,UWDS,SWDS)
        WDNF=NORMAL(NWDF,UWDF,SWDF)
*ESTIMATOR ERROR - INNOVATIONS IN SURGE, SWAY, AND YAW
        INX=XT-XE
        INY=YT-YE
        INP=PT-PE
*CURRENT CORRECTION (AS APPLIED TO LF VESSEL MODEL)
        Q1=XD-UC
        Q2=YD-VC
*THRUSTER FORCE = BOW THRUSTER + STERN THRUSTER
        FT=BT+ST
*BOW THRUSTER CONTROL
        BTI= G21*EX+G22*EXXD+G23*EY+G24*EYYD+G25*EP+G26*EPPD
        BTII=BTI-(DY*(VCH)*ABS(VCH)+FWYS)
*       BTII=BTI-FWYS/2.0
        BT=LIMIT(BTL,BTR,BTII)
*STERN THRUSTER CONTROL
        STI= G31*EX+G32*EXXD+G33*EY+G34*EYYD+G35*EP+G36*EPPD
```

```
      STII=STI-(DY*(VCH)*ABS(VCH)+FWYS)
*     STII=STI-FWYS/2.0
      ST=LIMIT(STL,STR,STII)
*PROP CONTROL
      FPI= G11*EX+G12*EXXD+G13*EY+G14*EYYD+G15*EP+G16*EPPD
      FPII=FPI-(DX*UC*ABS(UCH)+0.75*FWXS)
*     FPII=FPI-FWXS
      FP=LIMIT(FPL,FPR,FPII)
*MOMENT CONTROL
      MT=78.88*BT-81.12*ST
SAMPLE
*TOTAL VESSEL MOTION MODEL - MEASUREMENTS IN SURGE, SWAY, AND YAW
      XT=X+XH+MNOIX
      YT=Y+YH+MNOIY
      PT=P+PH+MNOIP
*SAMPLED WIND FORCES AND MOMENT IN SURGE, SWAY, AND YAW
      FWXS=FWX
      FWYS=FWY
      MWS=MW
DERIVATIVE
*LOW FREQUENCY VESSEL MODEL
*LF SURGE
      X=INTGRL(X0,XD)
      XD=INTGRL(XD0,XDD)
      XDD=NOIX+(FWX+FP-DX*Q1*ABS(Q1)+MY*Q2*PD+MX*VC*PD)/MX
*LF SWAY
      Y=INTGRL(Y0,YD)
      YD=INTGRL(YD0,YDD)
      YDD=NOIY+(FWY+FT-DY*Q2*ABS(Q2)+MY*UC*PD+MX*Q1*PD)/MY
*LF YAW
      P=INTGRL(P0,PD)
      PD=INTGRL(PD0,PDD)
      PDD=NOIP+(-(MY-MX)*Q1*Q2-DP*ABS(PD)*PD+MC+MW+MT)/MP
*HIGH FREQUENCY VESSEL MODEL
*HF SURGE
      XH=INTGRL(0.0,XHD)
      XHD=INTGRL(0.0,XHDD)
      XHDD=-(WX**2)*XH+HNOIX-.2*XHD
*HF SWAY
      YH=INTGRL(0.0,YHD)
      YHD=INTGRL(0.0,YHDD)
      YHDD=-(WY**2)*YH+HNOIY-.2*YHD
*HF YAW
      PH=INTGRL(0.0,PHD)
      PHD=INTGRL(0.0,PHDD)
      PHDD=-(WP**2)*PH+HNOIP-.2*PHD
*HF WAVE FREQUENCY VARIATION MODEL
*FREQUENCY IN SURGE
      WX=INTGRL(W,WXD)
      WXD=NORMAL(NWX,UWX,SWX)
*FREQUENCY IN SWAY
      WY=INTGRL(W,WYD)
      WYD=NORMAL(NWY,UWY,SWY)
*FREQUENCY IN YAW
      WP=INTGRL(W,WPD)
```

```
      WPD=NORMAL(NWP,UWP,SWP)
*CURRENT MODEL IN EARTH COORDINATES
      XCED=INTGRL(XCI,XCEDD)
      XCEDD=CXNOI
      YCED=INTGRL(YCI,YCEDD)
      YCEDD=CYNOI
      PCED=INTGRL(PCI,PCEDD)
      PCEDD=CPNOI
*CURRENT MODEL IN SURGE, SWAY, AND YAW
      UC=XCED*DCOS(PT)+YCED*DSIN(PT)
      VC=-XCED*DSIN(PT)+YCED*DCOS(PT)
      MC=PCED
*WIND MODEL
*SLOWLY VARYING WIND VELOCITY
      WVS=INTGRL(IWVS,WVSD)
      WVSD=WVNS
*RAPIDLY VARYING WIND VELOCITY
      WVF=INTGRL(0.0,WVFD)
      WVFD=A1*WVF+WVNF
*SLOWLY VARYING WIND DIRECTION
      WDS=INTGRL(IWDS,WDSD)
      WDSD=WDNS
*RAPIDLY VARYING WIND DIRECTION
      WDF=INTGRL(0.0,WDFD)
      WDFD=A2*WDF+WDNF
*WIND ANGLE OF ATTACK
      BETA=WDS+WDF-PT
*WIND FORCE EQUATIONS IN SURGE, SWAY, AND YAW
      FWX=-F1*DCOS(BETA)*(WVS+WVF)**2
      FWY=-F2*DSIN(BETA)*(WVS+WVF)**2
      MW=F3*DSIN(BETA)*(WVS+WVF)**2
*KALMAN FILTER FOR VESSEL
*VESSEL KALMAN IN SURGE
      EX=RX-XE
      EXXD=RXD-XED
      AXE=(-DX*(XED-0.)*ABS(XED-0.)+MY*(YED-0.)*PED+MX*0.*PED)/MX
      BXE=(FP+FWXS)/MX
      XE=INTGRL(0.0,XED)
      XED=INTGRL(0.0,XEDD)+K11*(XT-XE)+K12*(YT-YE)+K13*(PT-PE)
      XEDD=AXE+BXE+K21*(XT-XE)+K22*(YT-YE)+K23*(PT-PE)
*VESSEL KALMAN IN SWAY
      EY=RY-YE
      EYYD=RYD-YED
      AYE=(-DY*(YED-0.)*ABS(YED-0.)+MX*(XED-0.)*PED+MY*0.*PED)/MY
      BYE=(FT+FWYS)/MY
      YE=INTGRL(0.0,YED)
      YED=INTGRL(0.0,YEDD)+K31*(XT-XE)+K32*(YT-YE)+K33*(PT-PE)
      YEDD=AYE+BYE+K41*(XT-XE)+K42*(YT-YE)+K43*(PT-PE)
*VESSEL KALMAN IN YAW
      EP=RP-PE
      EPPD=RPD-PED
      APE=(-(MY-MX)*(XED-0.)*(YED-0.)-DP*PED*ABS(PED))/MP
      BPE=(MWS+MT+0.)/MP
      PE=INTGRL(0.0,PED)
      PED=INTGRL(0.0,PEDD)+K51*(XT-XE)+K52*(YT-YE)+K53*(PT-PE)
```

```
      PEDD=APE+BPE+K61*(XT-XE)+K62*(YT-YE)+K63*(PT-PE)
*FILTER PREDICTION OF CURRENT OFFSET
*CURRENT PREDICTION IN SURGE
      CX=INX-XCH
      XCH=INTGRL(0.0,UCH)
      UCH=INTGRL(0.0,UCHD)+(C11*CX)
      UCHD=(C21*INX)
*CURRENT PREDICTION IN SWAY
      CY=INY-YCH
      YCH=INTGRL(0.0,VCH)
      VCH=INTGRL(0.0,VCHD)+(C32*CY)
      VCHD=(C42*INY)
*CURRENT PREDICTION IN YAW
      CP=INP-PCH
      PCH=INTGRL(0.0,PCHD)
      PCHD=INTGRL(0.0,PCHDD)+(C53*CP)
      PCHDD=(C63*CP)
*   TRANSFORM BACK TO VESSEL COORDINATES
      MCH=PCHD
CONTROL FINTIM=800.0,DELT=.10,DELS=1.0
METHOD RKSFX
SAVE 10.00,X,EX,FP,Y,EY,BT,ST,MT,P,EP,XT,YT,PT,XE,YE,PE,XH,YH,PH,...
      FWX,FWY,MW,XDD,XHDD,MC,UC,VC,UCH,VCH,INX,INY,INP,XED,YED,PED
*RINT UC,UCH,VC,VCH
GRAPH (G1,DE=TEK618) TIME(UN='SEC'),XT(UN='FT'),XE
LABEL (G1) XT VS TIME
GRAPH (G2,DE=TEK618) TIME(UN='SEC'),YT(UN='FT'),YE
LABEL (G2) YT VS TIME
GRAPH (G3,DE=TEK618) TIME(UN='SEC'),PT(UN='RAD'),PE
LABEL (G3) PT VS TIME
GRAPH (G4,DE=TEK618) TIME(UN='SEC'),FP(UN='LBF')
LABEL (G4) PROP CONTROL
GRAPH (G5,DE=TEK618) TIME,BT,ST
LABEL (G5) THRUSTER CONTROL
GRAPH (G6,DE=TEK618) Y(UN='FT'),X(UN='FT')
LABEL (G6) POSITION X VS Y
GRAPH (G7,DE=TEK618) XE,XED
LABEL (G7) PHASE PLANE
*GRAPH (G7,DE=TEK618) TIME,UC,UCH
*LABEL (G7) POSITION UC,UCH VS TIME
*GRAPH (G8,DE=TEK618) TIME,VC,VCH
*LABEL (G8) POSITION VC,VCH VS TIME
*GRAPH (G9,DE=TEK618) TIME,INX,INY
*LABEL (G9) ERROR RESIDUALS
*GRAPH (G8,DE=TEK618) TIME,Y,YH
*LABEL (G8) HIGH AND LOW FREQUENCY SWAY
*GRAPH (G9,DE=TEK618) TIME,P,PH
*LABEL (G9) HIGH AND LOW FREQUENCY YAW
END
STOP
```

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